

(Only for new nonprovisional applications under 37 CFR 1.53(b))

Total Pages in this Submission: 108

Box Patent Application
Washington, D.C. 20231

Method and Apparatus for Mapping Uncertainty and Generating a Map or a Cube Based on Conditional Simulation of Random Variables

Peter P. Van Bemmelen

☒ Continuation ☐ Divisional ☐ Continuation-in-part (CIP) of prior application No.:

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☐ Continuation ☐ Divisional ☒ Continuation-in-part (CIP) of prior application No.:

Application Elements

- Page 1 of 3

UTILITY PATENT APPLICATION TRANSMITTAL (Large Entity)

(Only for new nonprovisional applications under 37 CFR 1.53(b))

Docket No.
94.0027

Total Pages in this Submission
108

Application Elements (Continued)

3. ☒ Drawing(s) (when necessary as prescribed by 35 USC 113)
- a. ☐ Formal Number of Sheets _____
- b. ☒ Informal Number of Sheets 22
4. ☒ Oath or Declaration
- a. ☒ Newly executed (original or copy) ☐ Unexecuted
- b. ☐ Copy from a prior application (37 CFR 1.63(d)) (for continuation/divisional application only)
- c. ☒ With Power of Attorney ☐ Without Power of Attorney
- d. ☐ DELETION OF INVENTOR(S)
Signed statement attached deleting inventor(s) named in the prior application,
see 37 C.F.R. 1.63(d)(2) and 1.33(b).
5. ☐ Incorporation By Reference (usable if Box 4b is checked)
The entire disclosure of the prior application, from which a copy of the oath or declaration is supplied under Box 4b, is considered as being part of the disclosure of the accompanying application and is hereby incorporated by reference therein.
6. ☐ Computer Program in Microfiche (Appendix)
7. ☐ Nucleotide and/or Amino Acid Sequence Submission (if applicable, all must be included)
- a. ☐ Paper Copy
- b. ☐ Computer Readable Copy (identical to computer copy)
- c. ☐ Statement Verifying Identical Paper and Computer Readable Copy

Accompanying Application Parts

8. ☒ Assignment Papers (cover sheet & document(s))
9. ☐ 37 CFR 3.73(B) Statement (when there is an assignee)
10. ☐ English Translation Document (if applicable)
11. ☒ Information Disclosure Statement/PTO-1449 ☒ Copies of IDS Citations
12. ☐ Preliminary Amendment
13. ☒ Acknowledgment postcard
14. ☒ Certificate of Mailing
- ☐ First Class ☒ Express Mail (Specify Label No.): EI825189437US

UTILITY PATENT APPLICATION TRANSMITTAL (Large Entity)

(Only for new nonprovisional applications under 37 CFR 1.53(b))

Docket No.

94.0027

Total Pages in this Submission

108

Accompanying Application Parts (Continued)

15. ☐ Certified Copy of Priority Document(s) (if foreign priority is claimed)

16. ☒ Additional Enclosures (please identify below):

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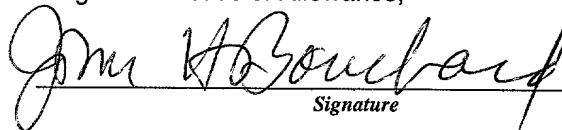
713-513-2515

Fee Calculation and Transmittal

CLAIMS AS FILED

For	#Filed	#Allowed	#Extra	Rate	Fee
Total Claims	41	- 20 =	21	x \$18.00	\$378.00
Indep. Claims	5	- 3 =	2	x \$78.00	\$156.00
Multiple Dependent Claims (check if applicable) <input type="checkbox"/>					\$0.00
BASIC FEE					\$690.00
OTHER FEE (specify purpose)					\$0.00
TOTAL FILING FEE					\$1,224.00

- ☐ A check in the amount of _____ to cover the filing fee is enclosed.
- ☒ The Commissioner is hereby authorized to charge and credit Deposit Account No. **07-1078** as described below. A duplicate copy of this sheet is enclosed.
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- ☐ Charge the issue fee set in 37 C.F.R. 1.18 at the mailing of the Notice of Allowance, pursuant to 37 C.F.R. 1.311(b).


Signature

Dated: March 7, 2000

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METHOD AND APPARATUS FOR MAPPING UNCERTAINTY
AND GENERATING A MAP OR A CUBE BASED ON
CONDITIONAL SIMULATION OF RANDOM VARIABLES

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CROSS REFERENCE TO RELATED APPLICATIONS

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This application is a Utility application of prior pending provisional application serial number 60/135,904, filed 05/25/99, and entitled "Uncertainty Mapping".

BACKGROUND OF THE INVENTION

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The subject matter of the present invention relates to a software based method and associated apparatus for mapping uncertainty by producing one or more "maps", such as a probability map or a cutoff map or a confidence limit map, and/or one or more cubes, based on the conditional simulation of a set of random variables.

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The estimation at any spatial location (x, y, z) of the value of a parameter (i.e., a random variable), such as porosity or permeability, from a set of scattered observations of data representing such a parameter may be achieved by a method known as "Kriging". For a reference which describes "Kriging", refer to either of the following two references: (1) Journel, A.G. "Fundamentals of Geostatistics in Five Lessons", Short course in Geology, vol 8, 44 pp, AGU, Washington, D.C. 1989, or

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(2) Deutsch, Clayton V. and Andre Journel, "GSLIB Geostatistical Software Library and User's Guide second edition", Oxford University Press, New York, Oxford, 1998; the disclosures in each of the above two references which discuss "Kriging"

are incorporated by reference into this specification. For example, if a set of scattered data samples represents porosity (obtained, for example, by mapping a cross section of an earth formation through which a plurality of wellbores are drilled as indicated in figures 4 and 5), when the cross section is gridded, the “Kriging” method can determine, at each intersection of the grid, the expected (mean) value of porosity and its standard deviation.

The result of estimating this value at a regular grid results in a smooth surface of the expected value generally following the data (see figures 4 through 16). If the principle of exactitude is applied, this surface will actually go through the data if the data falls on a grid location. The error variance is also calculated at each grid location. At the data locations, this error variance equals zero unless the observation error variance is included in the calculation, in which case, this is the error variance at the data locations.

It is common practice to render a more realistic estimate of the variable by randomizing the answer using the estimated error variance. This is called a ‘conditional simulation’ because it is conditioned by the data and produces one out of any number of possible realizations. It is then customary to assess the risk associated with exploitation of the estimated accumulation of ore, hydrocarbons or other valuable commodities by sampling a good many of the realizations and ranking them in low, medium, and high ranges, according to the economic value of the estimated deposits. This is a lengthy and costly procedure.

Therefore, a new method of mapping uncertainty is needed.

A method of mapping an earth formation has been disclosed in U.S. Patents 5,563,949 and 5,995,907. Another method for mapping an earth formation and generating a cube which contains a plurality of such maps is disclosed in prior pending application serial number 09/377,573, filed 08/19/99, and entitled “Seismic signal processing method and apparatus for generating a cube of variance values”.

SUMMARY OF THE INVENTION

Accordingly, it is a primary object of the present invention to provide a new method
5 for mapping uncertainty, the new method being based on the conditional simulation
of random variables.

In accordance with the above object of the present invention, it is a primary feature of
the present invention to generate one or more maps representing the characteristics at
10 each intersection of a gridded cross-section, where the gridded cross-section
represents a time slice or a horizon through an earth formation, in response to a
plurality of scattered data samples on such cross-section, where the data samples
represent a plurality of parameters located at a plurality of random locations on the
cross section, by performing the steps of: (a) obtaining a unique cumulative
15 distribution function associated with each intersection of the gridded cross-section in
the earth formation, (b) choosing a value from each of the cumulative distribution
functions at each of the intersections of the gridded cross section, and (c) assigning
such value to its respective intersection of the gridded cross section and assigning a
unique color to each such value, thereby generating a map illustrating the
20 characteristics of the cross section through the earth formation.

It is a further feature of the present invention to utilize the above referenced method
for generating one or more maps to also generate a cube, the cube including a
plurality of such maps which illustrate a set of characteristics associated with a
25 plurality of cross sections through an earth formation.

It is a further feature of the present invention to obtain the unique cumulative
distribution function associated with each intersection of the gridded cross-section by
first obtaining a unique probability density function associated each such intersection,
30 and then obtaining the unique cumulative distribution function from the probability

density function associated with each intersection of the gridded cross section through the earth formation.

It is a further feature of the present invention to generate one or more maps

- 5 representing the characteristics at each intersection of a gridded cross section representing a time slice or a horizon in an earth formation in response to a plurality of scattered data samples which represent a plurality of parameters located at a plurality of random locations on said cross section by performing the steps of:
- (a) gridding the cross section thereby creating a plurality of intersections on said cross section, (b) Kriging the gridded cross section thereby producing a plurality of expected (mean) values of the parameter and a corresponding plurality of standard deviations associated, respectively, with the plurality of intersections on the gridded cross section in response to the plurality of scattered data samples, (c) generating a plurality of probability density functions corresponding, respectively, to the plurality of expected values and standard deviations which are associated, respectively, with the plurality of intersections of the gridded cross section, a unique probability density function being associated with each intersection of the gridded cross section, (d) integrating each of the probability density functions at each of the intersections of the gridded cross section to generate a plurality of cumulative distribution functions associated, respectively, with the plurality of intersections, a unique cumulative distribution function being associated with each intersection of the gridded cross section, (e) choosing a value from each of the cumulative distribution functions at each of the intersections of the gridded cross section, and (f) assigning such value to its associated intersection of the gridded cross section and assigning a unique color to each such value, thereby generating a map illustrating the characteristics of the cross section (which could represent a time slice or a horizon) through the earth formation.

It is a further feature of the present invention to generate one or more maps

- representing the characteristics at each intersection of a cross-section in an earth formation in response to a plurality of scattered data samples, wherein the choosing step (e) for choosing a value from each of the cumulative distribution functions
- 30

(CDF) at each of the intersections of the gridded cross section comprises the step of selecting a cutoff value of a parameter on the x-axis of a CDF and choosing the associated value (Pcu) on the y-axis of the CDF, one minus such value $[(1-P_{cu})]$ representing the probability that the parameter is greater than the cutoff.

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It is a further feature of the present invention to generate one or more maps representing the characteristics at each intersection of a cross-section in an earth formation in response to a plurality of scattered data samples, wherein the choosing step (e) for choosing a value from each of the cumulative distribution functions

10 (CDF) at each of the intersections of the gridded cross section comprises the step of selecting a value of probability on the y-axis of the CDF and choosing its associated value "Xp" of a parameter on the x-axis of the CDF.

It is a further feature of the present invention to generate one or more maps

15 representing the characteristics at each intersection of a cross-section in an earth formation in response to a plurality of scattered data samples, wherein the choosing step (e) for choosing a value from each of the cumulative distribution functions (CDF) at each of the intersections of the gridded cross section comprises the step of selecting a confidence range (e.g., 90%) on the y-axis of the CDF and choosing one of
20 three values on the x-axis of the CDF: a lower limit, a spread, and an upper limit of such parameter on the x-axis of the CDF.

It is a further feature of the present invention to generate one or more maps

25 representing the characteristics at each intersection of a cross-section in an earth formation in response to a plurality of scattered data samples, wherein the value selected via the choosing step (e) undergoes an affine correction, the value assigned to its associated intersection of the gridded cross section via the assigning step (f) being a "corrected value" which underwent a correction via the affine correction.

30 It is a further feature of the present invention to generate a cube representing a cubic volume through an earth formation which includes a plurality of gridded cross

sections, where each gridded cross section includes a plurality of intersections, by performing the step of assigning the aforementioned “corrected value” to each intersection of each gridded cross section through a cubic volume of the earth formation.

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In accordance with this object and other objects and features of the present invention, a new method is presented to produce probability, cutoff, confidence limit and connectivity maps in one single operation. In addition, the new method also produces a cube containing a plurality of said maps, where each of the maps in the cube may represent the probability map, the cutoff map, or the confidence limit map. This is accomplished by using the estimated gaussian distribution at each intersection of the grid given by an expected value and an error variance. For computations on non-gaussian problems, the data may be converted to gaussian by using the normal score transform [refer to the following reference: Deutsch, Clayton V. and Andre Journal, “GSLIB Geostatistical Software Library and User’s Guide second edition”, Oxford University Press, New York, Oxford, 1998, page 141, the disclosure of which is incorporated by reference into this specification]. The answers may be converted back to the prior distribution by a back transform.

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More particularly, given a cross section through an earth formation, which cross section could represent a time slice or horizon in the earth formation, when a plurality of the random variables or parameters are associated with the cross section (for example, porosity or permeability), one or more maps can be generated, where each map illustrates a set of characteristics of that cross section, and a cube can also be generated, where the cube includes a plurality of such maps corresponding to a plurality of the cross sections through the earth formation. This can be accomplished by: (1) gridding the cross section thereby producing a gridded cross section including the plurality of associated random variables, the gridded cross section including a plurality of intersections, (2) using the random variables or parameters (such as porosity) on the cross section, obtaining a corresponding plurality of parameters at each of the intersections of the gridded cross section by “Kriging” the plurality of

random variables on the gridded cross section, the plurality of parameters at each intersection of the gridded cross section including a unique expected value of the parameter (i.e., the mean value) and a unique standard deviation, the unique expected value and the unique standard deviation at each intersection of the gridded cross section corresponding to a unique probability density function at each intersection, (3) integrating the probability density function at each intersection of the gridded cross section to obtain a unique cumulative distribution function at each intersection of the gridded cross section, (4) from the unique cumulative distribution function at each intersection of the gridded cross section, obtaining a value from that cumulative distribution function, a plurality of values being obtained which are associated, respectively, with the plurality of intersections of the gridded cross section, (5) correcting the plurality of values obtained from the corresponding plurality of cumulative distribution functions and associated, respectively, with the plurality of intersections by using an “affine correction” thereby producing a plurality of ‘corrected values’ corresponding, respectively, to the plurality of intersections of the gridded cross section, and (6) assigning each of the ‘corrected values’ to a particular intersection of the gridded cross section, and assigning a unique color to each such corrected value.

The above step (4), for obtaining a value from the cumulative distribution function, would include: (4a) selecting a cutoff on the x-axis of the cumulative distribution function and determining a probability “Pcu” on the y-axis, (1-Pcu) being the ‘value’ which represents the probability that the parameter is greater than the cutoff, or (4b) selecting a probability on the y-axis of the cumulative distribution function and determining a cutoff “Xp” on the x-axis of the cumulative distribution function, “Xp” being the ‘value’ which represents a cutoff, or (4c) selecting a confidence limit range on the y-axis of the cumulative distribution function, and choosing three ‘values’ from the x-axis of the cumulative distribution function: the “lower limit”, the “spread”, and the “upper limit”.

A lower cutoff map is generated by plugging in the desired probability and measuring the quantity via the local cumulative distribution function (cdf). In this manner, we produce a map of lower cutoff values for the desired probability. We can then say that, at any given (x, y, z) location, the content is at least the cutoff value with a probability of, for example, ninety percent. A lower cutoff cube can be generated from a plurality of the lower cutoff maps. A probability map is generated by plugging in the desired lower cutoff and evaluating the probability at any (x, y, z) location, again using the gaussian cumulative distribution function (cdf). A probability cube can be generated from a plurality of the probability maps.

Confidence limit maps are obtained by plugging in half the compliment of the confidence level and one minus this measure to the lower and upper limit of the cumulative distribution function (cdf). The difference between those limits is the data range for the given confidence level. For example, a confidence level of 90% would correspond to .05 and .95 on the cdf. A confidence limit cube can also be generated from a plurality of the confidence limit maps. To compensate for the smoothing effect of randomizing within the estimated error variance, an affine correction is applied. This is accomplished by co-generating one realization without feeding the newly estimated nodes back into the simulation. The mean and the standard deviation of this realization are then calculated and compared with the mean and the standard deviation of the data. The correction ensures that the resulting maps are derived from the same global mean and standard deviation as the original data. A connectivity map may be produced from a permeability cutoff map for a given probability by superimposing an arbitrary bound above which the formation is said to be permeable and below which it is impermeable. We may use indicators such as a “one” to denote permeability and a “zero” to denote impermeability. In this fashion, a reservoir may be divided into several unconnected compartments, which will influence the economics of the extraction of hydrocarbons. Permeability cutoff maps may be submitted to a fluid flow simulator to estimate the minimum production for a given acceptable probability or risk. It should be remembered, however, that, although this is a lower cutoff surface, it is smooth and does not represent the natural irregularities we expect in the reservoir.

Further scope of applicability of the present invention will become apparent from the detailed description presented hereinafter. It should be understood, however, that the detailed description and the specific examples, while representing a preferred
5 embodiment of the present invention, are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will become obvious to one skilled in the art from a reading of the following detailed description.

10 BRIEF DESCRIPTION OF THE DRAWINGS

A full understanding of the present invention will be obtained from the detailed description of the preferred embodiment presented hereinbelow, and the accompanying drawings, which are given by way of illustration only and are not
15 intended to be limitative of the present invention, and wherein:

Figure 1 illustrates a workstation or other computer system which stores a novel
"uncertainty mapping" software which is processed by a processor in response to input data comprised of randomly scattered data samples;

20 Figures 2 and 3 illustrates a flowchart used for discussion of the production of the Probability maps by the uncertainty mapping software of figure 1;

Figures 4 through 16 illustrates several figures which are used during the discussion
25 of the production of the Probability maps by the uncertainty mapping software of figure 1;

Figures 17 and 18 illustrate figures which are used during the discussion of the
production of the cutoff map by the uncertainty mapping software of figure 1;

Figures 19 through 22 illustrate figures which are used during the discussion of the production of the confidence limit map by the uncertainty mapping software of figure 1;

- 5 Figure 23 illustrates the affine correction applied to the $(1-P_{cu})$, the X_p , the lower limit, the spread, and the upper limit;

- Figures 24 through 28 illustrate the corrected values of $(1-P_{cu})$, X_p , lower limit, spread, and upper limit, corrected by the affine correction, which are assigned to and
10 plotted on a gridded cross section through an earth formation;

Figures 29 through 32 illustrates the function of the affine correction;

- Figures 33 and 34 illustrates different examples of probability maps which are
15 generated by the uncertainty mapping software of the present invention;

- Figure 35 illustrates Kriging with exactitude, including estimated value (fig 35a), error variance and without exactitude (fig 35b), expected value (fig 35c), and error
20 variance of the expected value (fig 35d);

- Figures 36 through 43 illustrate how the methods discussed in this specification in connection with figures 1 through 35, for generating a probability map and a lower cutoff map and a confidence limit map, may be used for generating a cube which represents a cubic volume of an earth formation and illustrates a set of characteristics
25 of the earth formation within that cube; and

Figures 36 through 43 illustrate how a cube is generated given the methods discussed with reference to figures 1 through 35 for determining a 'corrected value' to assign to each intersection of a gridded cross section.

DESCRIPTION OF THE PREFERRED EMBODIMENT

In the prior art involving Conditional Simulation, the estimation at any spatial

5 location (x,y,z) of the value of a gaussian random variable from a set of scattered data samples is accomplished by a method known as “Kriging” [as previously mentioned, refer to either: (1) Journel, A.G. “Fundamentals of Geostatistics in Five Lessons”, Short course in Geology, vol 8, 44 pp, AGU, Washington, D.C. 1989, or (2) Deutsch, Clayton V. and Andre Journel, “GSLIB Geostatistical Software Library and User’s
10 Guide second edition”, Oxford University Press, New York, Oxford, 1998]. The result of estimating this value at a regular grid results in a smooth surface of the expected value generally following the data. If the principle of exactitude is applied, this surface will actually go through the data if the data falls on a grid location. The error variance is also calculated at each grid location. At the data locations, this error
15 variance equals zero unless the observation error variance is included in the calculation, in which case, this is the error variance at the data locations. It is common practice to render a more realistic estimate of the variable by randomizing the answer using the estimated error variance. This is called a ‘conditional simulation’ because it is conditioned by the data and produces one out of any number
20 of possible realizations. For a teaching on ‘conditional simulation’, refer to: “Fundamentals of Geostatistics in Five Lessons”, by A. G. Journel, Short course in Geology, vol 8, 40 pp, AGU, Washington, D.C. 1989.

For example, in order to “Krig the expected value and standard deviation”, consider
25 the following equations [refer to reference (2): Deutsch, Clayton V. and Andre Journel, “GSLIB Geostatistical Software Library and User’s Guide second edition”, Oxford University Press, New York, Oxford, 1998, page 14, equations II.12 and II.13]:

$$30 \quad Z_{SK}^*(u) = \sum \lambda_{\alpha}(u) Z(u_{\alpha}) + (1 - \sum \lambda_{\alpha}(u)) m \quad (1)$$

The corresponding minimized estimation variance is:

$$\sigma_{sk}^2(u) = C(0) - \sum \lambda_{\alpha}(u)C(u-u_{\alpha}) \quad (2)$$

For ordinary “Kriging”, the sum of the set of weights is constrained to unity, which leads to:

$$5 \quad Z_{OK}^*(u) = \sum \lambda_{\alpha}(u)Z(u_{\alpha}) \quad (3)$$

where:

$Z_{SK}^*(u)$ = estimate of unsampled data value at location ‘u’ using “simple kriging”,

$\lambda_{\alpha}(u)$ = weights determined to minimize the estimation variance,

$Z(u_{\alpha})$ = neighboring data values used in the estimate where $\alpha = 1, \dots, n$,

10 m = the a priori known stationary mean of the data, and

$C(u-u_{\alpha})$ = covariance.

The “Kriging” estimate is also known as the ‘expected value’ or the ‘local mean’ of the estimated distribution of the data, and the estimation variance as the squared standard deviation of the distribution:

$$\mu_1 = \sum \lambda_{\alpha}(u)Z(u_{\alpha}) \quad (4)$$

Using the mean and the standard deviation, we may now execute a conditional stochastic simulation as follows:

$$xp = F^{-1}\{rand[p(011)]\} \quad (5)$$

$$20 \quad \xi = xp \bullet \sigma_1 + \mu_1 \quad (6)$$

where:

F^{-1} = inverse gaussian transform,

μ_1 = estimated local mean,

σ_1 = estimated local standard deviation,

25 xp = data value corresponding to p,

p = randomized probability, and
 ξ = estimated stochastic variable.

In accordance with the present invention, a new method and associated apparatus will
5 generate probability maps, cutoff maps, and confidence limit maps in one single
operation. In addition, in accordance with the present invention, given the novel
methods of the present invention for generating the probability maps, cutoff maps,
and confidence limit maps, the new method and apparatus of the present invention
will also generate a cube which illustrates a set of earth formation characteristics
10 disposed within a cubic volume of an earth formation, the cube including a plurality
of gridded cross sections, the grid of each cross section including a plurality of
intersections, the novel method of the present invention generating a 'corrected value'
for each intersection of each grid of each cross section in the cube.

15 Referring to figure 1, a computer system (e.g., a workstation computer system) is
illustrated and it includes a processor 10 connected to a system bus 12, a recorder or
display device 14 connected to the system bus 12, a memory or other storage device
(e.g., a computer readable medium) 16 connected to the system bus 12, and a source
of input data 18 comprised of a set of randomly scattered data samples 18, such as the
20 randomly scattered data samples shown in figures 4, 5, and 6. A CD-Rom 20 stores a
novel software known as the "uncertainty mapping software", the uncertainty
mapping software on the CD-Rom 20 being loaded into the computer system and
stored in the memory 16 of the computer system. Now that the software is loaded
into the computer system, the "uncertainty mapping software" will hereinafter be
25 referred to as the "uncertainty mapping software 16".

The computer system of figure 1 may be a personal computer (PC), a workstation, a
mainframe, etc. Examples of possible workstations include a Silicon Graphics Indigo
2 workstation and a Sun SPARC workstation. The processor 10 of the computer

system may be, for example, a microprocessor, microcontroller, or a mainframe or workstation processor. The memory 16 may be, for example, a hard disk, ROM, CD-Rom, DRAM, or other RAM, flash memory, magnetic storage, optical storage, registers, or other volatile and/or non-volatile memory.

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When the uncertainty mapping software 16 of the present invention is executed by the processor 10 of figure 1, the processor 10 will generate and display (via the recorder or display device 14 of figure 1) three different types of maps: (1) Probability maps, (2) Lower cutoff maps, and (3) Confidence limit maps (also called “confidence maps”) in one single operation. In addition, the processor 10 will generate and display the cube which illustrates the set of earth formation characteristics disposed within a cubic volume of an earth formation. The cube and each of the three different types of maps will be discussed in the following paragraphs.

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Referring to figures 2 and 3, when the uncertainty mapping software 16 of figure 1 produces the cube and the Probability maps and the lower cutoff maps and the confidence limit maps, the computer system of figure 1 executes the uncertainty mapping software 16 of the present invention. When executed, the uncertainty mapping software 16 performs a new method which uses the estimated gaussian distribution at each grid location (intersection) given by the expected value and the error variance. When the Uncertainty Mapping Software 16 is executed by the processor 10 of figure 1, the new method that is performed for generating a new and novel “cube”, as well as the “probability map”, “lower cutoff map” and “confidence limit map”, is illustrated in the flowchart/block diagram shown in figures 2 and 3.

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The novel method of the present invention for generating the maps will be first discussed. When these novel methods for generating the maps is understood, the novel method for generating the cube will be discussed.

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In figures 2 and 3, referring initially to figure 2, each probability value [“(1-Pcu)”] on the “Probability map”, and each lower cutoff “Xp” on the “lower cutoff map”, and

each “lower limit, spread, and upper limit” on each of three types of “confidence limit maps” (located at each intersection of a grid imposed on the map) is determined by performing the following method steps:

5 (1) Using a horizontal slice through a predetermined volume of earth including a plurality of wellbores, generate a cross section which includes a plurality of parameter data, such as porosity, block 22;

(2) grid the cross section, block 24;

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(3) Provide the gridded cross section including the plurality of parameter data representing scattered data samples 44a, 44b, 44c, and 44d as input data to a Kriging algorithm, execute the Kriging algorithm using that input data, and generate a second gridded cross section where each intersection of the second gridded cross section including a “particular intersection” has an expected (mean) value of that parameter and a standard deviation; generate a Probability Density Function (PDF) from each expected value and standard deviation associated with each of the intersections of the grid, block 26;

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(4) Integrate each Probability Density Function (PDF) to obtain a Cumulative Distribution Function (CDF) [recall that the area under the PDF curve is represented by the CDF], block 28;

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(5) Input a cutoff along the x-axis of the CDF and obtain a probability “Pcu” on the y-axis, block 30;

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(6) Correct the probability “Pcu” by performing an “affine correction” on the probability Pcu, block 37; and

(7) In figure 3, assign the corrected value “(1-Pcu) [corrected]” to the “particular intersection” and assign a unique color to that corrected value, block 39 in figure 3.

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The probability “(1-Pcu)” represents the probability that a parameter is greater than the cutoff. In our examples to follow, the “parameter” will be porosity; however, understand that the above method will work in connection with other types of parameters, including but not limited to porosity.

In addition, each lower cutoff “Xp” on the “lower cutoff map” (located at each intersection of a grid imposed on the map) is determined by performing the following additional method steps:

(8) In figure 2, input a ‘probability’ along the y-axis of the cumulative distribution function (CDF) and obtain a lower cutoff “Xp” on the x-axis of the CDF, block 32, figure 2;

(9) Correct the lower cutoff “Xp” by performing an “affine correction” on the lower cutoff “Xp”, block 37; and

(10) In figure 3, assign the corrected value “Xp (corrected)” to the “particular intersection” and assign a unique color to that corrected value, block 41 in figure 3.

In addition, each “lower limit”, “spread”, and “upper limit” on three different types of “confidence limit maps” (located at each intersection of a grid imposed on the map) is determined by performing the following additional method steps:

(11) In figure 2, choose a “confidence level” on the y-axis of the CDF and obtain a “lower limit”, a “spread”, and an “upper limit” on the x-axis of the CDF, block 35;

(12) Correct the “lower limit”, the “spread”, and the “upper limit” by performing an “affine correction” on the “lower limit”, the “spread” and the “upper limit”, block 37;

(13) In figure 3, assign the corrected value “lower limit (corrected)” to the “particular intersection” and assign a unique color to that corrected value, block 43 in figure 3,

(14) assign the corrected value “spread (corrected)” to the “particular intersection”

5 and assign a unique color to that corrected value, block 45 in figure 3, and

(15) assign the corrected value “upper limit (corrected)” to the “particular intersection” and assign a unique color to that corrected value, block 47 in figure 3.

10 Each of these steps will be discussed in detail with reference to figures 4 through 32.

Referring to figures 4 through 32, and referring initially to figure 4, block 22 of figure 3 indicates that, using a horizontal slice through a predetermined volume of earth including a plurality of wellbores, a cross section through that earth volume is

15 generated, the cross section including a plurality of parameter data. One example of that parameter data is “porosity”. However, it should be understood that the method and associated apparatus of the present invention, illustrated in figures 2 and 3, will also work in connection with other types of parameter data (other than porosity, which is being used by way of example only). The parameter data in the cross section

20 represents the randomly scattered data samples 18 of figure 1. In figure 4, the predetermined volume of earth 34 has a cross section 36 passing therethrough. A plurality of wellbores 38 have been drilled in that volume of earth 34, the wellbores 38 passing through the cross section 36. In figure 5, one of those wellbores 38a is illustrated. The cross section 36 passes through the wellbore 38a of figure 5. A well

25 logging tool 40 in the wellbore 38a generates a well log 42. The y-axis of that well log 42 represents units of a particular parameter (the x-axis being units of depth). In our example, we use the following parameter, but only by way of example for purposes of this discussion: porosity. Therefore, in figure 5, the intersection between the cross section 36 and the well log 42 represents a particular parameter value

30 (e.g., porosity), as indicated by the “X” 44. As a result, in figure 4, the cross section 36 includes a plurality of parameter values 44a, 44b, 44c, and 44d (of porosity, which

parameter is being used in our example for purposes of discussion only). In figure 6, that cross section 36 is illustrated again, and the plurality of parameter values (e.g., of porosity) 44a through 44d from figure 4 are located and illustrated in that cross section 36.

5

In figure 6, the cross section 36 of figure 6 including the plurality of parameter values (e.g., of porosity) 44a through 44d in that cross section represent the “randomly scattered data samples” 18 of figure 1.

10 In figures 2 and 3, blocks 24, 26, 28, 30, 32, 35, 37, 39, 41, 43, 45, and 47 collectively comprise the “Uncertainty mapping software” 16 stored in the memory 16 of figure 1. Blocks 24, 26, 28, 30, 32, 35, 37, 39, 41, 43, 45, and 47 of figures 2 and 3 representing the Uncertainty Mapping Software 16 of figure 1 are discussed below with reference to figures 7 through 28 of the drawings.

15

Recall block 24 of figure 2: “grid the cross section”. Therefore, in figure 7, the first task at this point is to grid the cross section 46. In figure 7, grid lines 48 are drawn in the cross section 46, but the parameter values (of porosity in our example) 44a through 44d do not fall on an intersection of the grid 48. In accordance with block 24 of figure 2, the cross section 36 has been gridded as shown in figure 7.

20

Recall block 26 of figure 2: provide the gridded cross section including the plurality of parameter data as input data to a Kriging algorithm, execute the Kriging algorithm using that input data, and generate a second gridded cross section where each intersection of the second gridded cross section including a “particular intersection” has an expected (mean) value of that parameter and a standard deviation; and generate a Probability Density Function (PDF) from each “expected value/standard deviation” associated with each of the intersections.

25

30 In figure 8, the gridded cross section of figure 7 including the plurality of parameter values (e.g., of porosity data) 44a through 44d are provided as input data to a Kriging

Algorithm 50 (the Kriging algorithm has already been discussed in the above paragraphs). The Kriging algorithm is executed using that input data, and, responsive thereto, the Kriging algorithm generates a second gridded cross section 52 as shown in figure 9, where each intersection of the second gridded cross section 52 (which includes a particular intersection 54) has two values corresponding thereto: (1) an expected (mean) value of the parameter (in our example, an expected value of porosity), and (2) a standard deviation, block 56 of figure 9. That is, each intersection 54, 58, 60, 62, ..., etc of the second gridded cross section 52 has its own "expected value" of a parameter and its own "standard deviation" corresponding thereto. The Kriging algorithm 50 performs a type of interpolation, using the parameter values (of porosity in our example) 44a, 44b, 44c, and 44d, to determine a corresponding expected (mean) value of a parameter at each intersection 54, 58, etc, and a corresponding value of "standard deviation" at each intersection 54, 58, etc, of the second gridded cross section 52 in figure 9. Since we are using porosity by way of example only, at each intersection 54, 58, etc, of figure 9, a unique expected (mean) value of porosity and a unique standard deviation will associated with each intersection of the grid shown in figure 9.

In figure 10, let us examine, as an example, the intersection 54 of the second gridded cross section 52 of figure 9. Intersection 54 now has two values of data associated therewith: (1) a "particular expected (mean) value" of a parameter (such as "porosity" in our example), where the expected value of the parameter is determined using an interpolation technique performed by the Kriging algorithm 50 which utilizes the randomly scattered parameter values (of porosity in our example) 44a-44d of figure 6, and (2) a "particular standard deviation" (also determined by the Kriging algorithm 50), block 64 of figure 10.

In figure 10a, using the "particular expected (mean) value" and the "particular standard deviation" which are both associated with intersection 54 and which were both determined above with reference to figures 9 and 10, a "particular Probability Density Function (PDF)" can now be determined, and that "particular Probability

Density Function (PDF)” will now be associated with intersection 54. That
“particular Probability Density Function (PDF)” is illustrated in figure 10a.

In figures 11, 12, and 13, the “particular Probability Density Function (PDF)” shown
in figure 10a, which is specifically associated with intersection 54 of the gridded cross
section shown in figure 10, is illustrated again in figure 11 for purposes of this
discussion. Recall block 28 of figure 2: “integrate each Probability Density Function
(PDF) to obtain a “Cumulative Distribution Function”. Therefore, in figure 11,
integrate the Probability Density Function to thereby obtain the “Cumulative
Distribution Function” (CDF), block 66 of figure 12. That “Cumulative Distribution
Function (CDF)” is illustrated in figure 13. However, since the “particular
Probability Density Function (PDF)” of figures 10a and 11 is specifically associated
with intersection 54 of the gridded cross section shown in figure 10, the “Cumulative
Distribution Function (CDF)” of figure 13 is also specifically associated with
intersection 54 of the gridded cross section shown in figure 10.

Probability Map

A “probability map” is generated by plugging in the desired lower cutoff and
evaluating the probability “n” at any (x, y, z) location. That is, consider the following
equations:

$$P_{100n}(xyz) = p\{\xi > colxyz\} \quad (7)$$

$$xp = (co - \mu) / \sigma \quad (8)$$

$$n = F(xp) \quad (9)$$

where:

F = gaussian transform

Co = desired cutoff

P = calculated probability

σ = standard deviation

μ = mean

ξ = estimated variable

5 In figures 2 and 14, recall block 30 of figure 2: "Input a 'cutoff' along the x-axis of the CDF and obtain a 'probability (1-Pcu)' on the y-axis". Therefore, in figure 14, block 68, the user/operator inputs a 'cutoff' X_p along the x-axis of the CDF (e.g., 10%) and obtains a probability "Pcu" on the y-axis. The probability "Pcu" represents the probability that the parameter (e.g., porosity) is less than the cutoff
10 "Xp". Therefore, when the probability "Pcu" is determined, the probability "(1-Pcu)" must represent the probability that the parameter is greater than the cutoff "Xp".

In figure 15, for example, the user inputs a "cutoff" (e.g., "Xp") on the x-axis of the
15 Cumulative Distribution Function (CDF) and obtains a probability "Pcu" on the y-axis of the Cumulative Distribution Function of figure 15. The probability "Pcu" represents the probability that the parameter (e.g., porosity) is less than the cutoff "Xp". In order to obtain the probability that the parameter is greater than the cutoff "Xp", subtract "Pcu" from "1" to obtain "(1-Pcu)", as shown in figure 15.

20 In figures 15 and 16, recall that the CDF of figure 15 is specifically associated with intersection 54 of the gridded cross section 52. In addition, recall that, for intersection 54 of the gridded cross section 52 of figure 10, "(1-Pcu)" is the probability that the parameter (such as porosity) is greater than the cutoff "Xp".

25 In figure 16, in order to plot one point on a specific "Probability map" which would represent or illustrate the probability that a parameter, such as porosity, is greater than a cutoff "Xp", assign and plot and superimpose onto intersection 54 of the gridded cross section 52 the value "(1-Pcu)" and then assign a unique color to intersection 54
30 which would specifically identify that value "(1-Pcu)".

Lower Cutoff maps

Referring to figure 17, when producing Lower Cutoff maps, by transforming the
5 desired probability using the estimated local mean and standard deviation, the new
method and apparatus of the present invention will produce a map of lower cutoff
values. We can then say that, at any given (x, y) location, the “content” at that given
(x, y) location (i.e., the value of a parameter, such as porosity, at that intersection,
such as the intersection 54 of the gridded cross section 52) is at least the cutoff value
10 of the parameter with a probability of, for example, ninety percent (i.e., $n = 0.9$).

That is, for a lower cutoff ϕ and a given probability P_{100n} :

$$\text{co}(xyz) = xp \{p = .9 \mid xyz\} \quad (10)$$

$$xp = F^{-1}(p) \quad (11)$$

$$\text{co} = xp \cdot \sigma + \mu \quad (12)$$

where

F^{-1} = inverse gaussian transform

co = calculated cutoff

p = desired probability

σ = standard deviation

μ = mean

In figures 2, 17, and 18, recall block 32 of figure 2: Input a ‘probability’ along the
y-axis of the CDF and obtain a lower cutoff “Xp” on the x-axis of the CDF.

In figure 17, input a probability “Pcu” on the y-axis of the Cumulative Distribution
Function (CDF) and obtain a lower cutoff “Xp” on the x-axis of the CDF. In

figure 18, since the CDF of figure 17 is specifically associated with intersection 54 of
the gridded cross section 52, in order to plot one point on a specific “lower cutoff

map”, assign and plot and superimpose onto intersection 54 the value “Xp” and assign a unique color which will specifically identify the value “Xp”. As a result, we can say that, at intersection 54 of the gridded cross section 52 in figure 18, the probability is “Pcu” that the value of a parameter, such as porosity, at the intersection 54 is at least the cutoff value “Xp”.

Confidence Limit maps

Referring to figure 19, when producing Confidence limit maps, a Confidence limit is obtained (i.e., a lower limit, an upper limit, and a spread) by using “half the compliment of the confidence level” and “one minus this measure” (on the y-axis of the CDF) to thereby produce, on the x-axis of the CDF: (1) a ‘lower limit’ of the ‘content’ or ‘value of a parameter’, and (2) an ‘upper limit’ of the ‘content’ or ‘value of the parameter’. The difference between these two lower and upper limits is the data range (or ‘spread’) for the given confidence level. That is, for Lower and Upper Bounds for P_{100n} :

$$xp_u = F^{-1}(p_u) \quad (13)$$

$$co_u = xp_u \cdot \sigma + \mu \quad (14)$$

$$xp_l = F^{-1}(p_l) \quad (15)$$

$$co_l = xp_l \cdot \sigma + \mu \quad (16)$$

$$\delta = xp_u - xp_l \quad (17)$$

where

p = confidence level

σ = standard deviation

μ = mean

xp_u = upper confidence limit

x_{p_l} = lower confidence limit

co_u = upper cutoff

co_l = lower cutoff

δ = spread

In figure 2, recall block 35: choose a “confidence level on the y-axis of the CDF and obtain a “lower limit”, a “spread”, and an “upper limit” on the x-axis of the CDF.

In figure 19, for example, assume a given confidence level “p” of 90%, as illustrated in figure 19. The confidence limits are chosen symmetrically about the 50% probability point on the vertical axis. For a confidence level of 90%, this results in an upper confidence limit of $50 + 90/2 = 95\%$ and a lower confidence limit of $50 - 90/2 = 5\%$. Refer now to figure 19, and note the upper and lower values on the y-axis of the Cumulative Distribution Function (CDF); that is, the lower value on the y-axis of the CDF is 5% and the upper value on the y-axis of the CDF is 95%.

Starting at the 5% value on the y-axis of the CDF of figure 19, intersect the CDF curve in figure 19 and note the “lower limit” on the x-axis of the CDF in figure 19. Similarly, starting at the 95% value on the y-axis of the CDF of figure 19, intersect the CDF curve in figure 19 and note the “upper limit” on the x-axis of the CDF curve in figure 19. Furthermore, in figure 19, note that the difference between the “lower limit” and the “upper limit” on the x-axis of the CDF of figure 19 is called the “spread”.

Referring to figure 20, the “lower limit” is plotted and assigned to intersection point 54, and a unique color is assigned to that “lower limit”.

Referring to figure 21, the “spread” is plotted and assigned to intersection point 54, and a unique color is assigned to that “spread”.

Referring to figure 22, the “upper limit” is plotted and assigned to intersection point 54, and a unique color is assigned to that “upper limit”.

In figure 2, recall the “affine correction” block 37.

5

Referring to figure 23, the values of ‘(1-Pcu)’, ‘Xp’, ‘lower limit’, ‘spread’, and ‘upper limit’, which are assigned to intersection point 54 in figures 16, 18, 20, 21, and 22, respectively, must now undergo an “affine correction”. The “affine correction” will be discussed in detail below with reference to figure 29; however, suffice it to say

10

at this point that the mean and the standard deviation associated with each of the original data (in figure 6) and each of the “Kriged” data (in figure 9) are not the same.

That is, after Kriging (figure 8), the mean and standard deviation of each of the Kriged data (figure 9) is less than the mean and standard deviation of each of the original data (figures 6 and 7). Therefore, in order to remedy this problem, the

15

values of ‘(1-Pcu)’, ‘Xp’, ‘lower limit’, ‘spread’, and ‘upper limit’ must undergo the “affine correction”, prior to plotting and assigning such values to the intersection point 54 of the gridded cross section 52, in order that the mean and standard deviation of each of the Kriged data after undergoing the “affine correction”

(figure 23) is equal to the mean and standard deviation of each of the original data

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(figures 6 and 7). In figure 23, therefore, each of the values ‘(1-Pcu)’, ‘Xp’, ‘lower limit’, ‘spread’, and ‘upper limit’ undergo the “affine correction”, block 70 of figure 23, thereby generating the following corrected values: ‘(1-Pcu)[corrected]’, ‘Xp(corrected)’, ‘lower limit (corrected)’, ‘spread (corrected)’, and ‘upper limit (corrected)’.

25

In figure 2, recall blocks 39, 41, 43, 45, and 47, wherein the corrected values ‘(1-Pcu)[corrected]’, ‘Xp(corrected)’, ‘lower limit (corrected)’, ‘spread (corrected)’, and ‘upper limit (corrected)’ are assigned to the particular intersection and a unique color is assigned to that corrected value.

30

Referring to figure 24, the corrected value “(1-Pcu)[corrected]” is plotted and assigned to intersection point 54, and a unique color is assigned to that corrected value.

- 5 Referring to figure 25, the corrected value “Xp(corrected)” is plotted and assigned to intersection point 54, and a unique color is assigned to that corrected value.

- 10 Referring to figure 26, the corrected value “lower limit (corrected)” is plotted and assigned to intersection point 54, and a unique color is assigned to that corrected value.

Referring to figure 27, the corrected value “spread (corrected)” is plotted and assigned to intersection point 54, and a unique color is assigned to that corrected value.

- 15 Referring to figure 28, the corrected value “upper limit (corrected)” is plotted and assigned to intersection point 54, and a unique color is assigned to that corrected value.

- 20 Referring to figure 29, regarding the “affine correction”, in order to compensate for the smoothing effect of Kriging on the estimated mean and variance, an “affine correction” is applied to each value [such as ‘(1-Pcu)’ and ‘Xp’ and ‘lower limit’ and ‘spread’ and ‘upper limit’] that is assigned to each intersection (such as intersection 54) of the gridded cross section 52 shown in figure 9 (and figures 16, 18, 20, 21, and 22). This is accomplished by co-generating the Kriged estimation grid. The mean and standard deviation of this Kriged estimation grid are then calculated and compared with the mean and standard deviation of the data. The correction ensures that the resulting maps are derived from the same global mean and standard deviation as the original data.

- 30 In order to Compensate for the smoothing effect for the lower cutoff map:

$$xp = F^{-1}(p) \quad (18)$$

$$co = xp \cdot \sigma_1 + \mu_1 \quad (19)$$

$$5 \quad co' = (\sigma'/\sigma) (co - \mu) + \mu' \quad (20)$$

where:

F^{-1} = inverse gaussian transform

co = calculated cutoff

p = desired probability

σ' = standard deviation of the original data

σ = standard deviation of the co-generated realization

μ' = mean of the original data

μ = mean of the co-generated realization

co' = corrected cutoff

In order to Compensate for the smoothing effect for the probability map:

$$co' = (\sigma/\sigma') (co - \mu') + \mu \quad (21)$$

$$xp = (co' - \mu_1) / \sigma_1 \quad (22)$$

$$p' = F(xp') \quad (23)$$

where:

F = gaussian transform

co = desired cutoff

σ' = standard deviation of the original data

σ = standard deviation of the co-generated realization

μ' = mean of the original data

μ = mean of the co-generated realization

co' = corrected cutoff

5 p' = corrected probability

In figure 29, for example, when the original data 36 (from figure 6 and 7), having a mean X and a standard deviation Y, are Kriged, via the Kriging Algorithm 50, the resultant Kriged data 52 is produced, where the resultant Kriged data 52 has a mean A and a standard deviation B, and where $A < X$ and $B < Y$. However, when the Kriged data undergoes the affine correction 70, the final result 72 has a mean X and a standard deviation Y. The corrected values of '(1-Pcu)[corrected]', 'Xp(corrected)', 'lower limit (corrected)', 'spread (corrected)', and 'upper limit (corrected)' correspond to the final result 72.

15 Referring to figures 29, 30, 31, and 32, an example of a Probability Density Function representing the original data 36 of figure 29 is shown in figure 30 and note that the mean is 4.3504 and the standard deviation is 6.7026. However, an example of a Probability Density Function representing the Kriged data 52 of figure 29 is shown in figure 31 and note that the mean is 2.5077 and the standard deviation is 2.9313 (which is less than the mean of 4.3504 and the standard deviation of 6.7026 of the original data 36 shown in figure 30). On the other hand, an example of a Probability Density Function representing the Final Result 72 of figure 29, after the affine correction 70 has been applied to the Kriged data 52, is shown in figure 32 and note that the mean is 4.3504 and the standard deviation is 6.7026 (which is equal to the mean of 4.3504 and the standard deviation of 6.7026 of the original data 36 shown in figure 30).

25 Referring to figures 33, 34, and 35, these figures will illustrate some of the above features.

30 Figure 33, which includes figures 33a, 33b, 33c, and 33d, illustrates (in figure 33a) a

“one-out-of-a hundred” realization generated with conditional simulation. Figure 33c shows a lower cutoff porosity map with a probability of .9 illustrating that the actual porosity will be higher. Figure 33d is the probability map for a user defined 10% lower cutoff porosity. Figure 33b is a spread in porosity for a confidence level of 90%.

Figure 34, which includes figures 34a, 34b, 34c, and 34d, shows probability maps for different porosity cutoffs. As one would expect, the probability to find higher porosity cutoffs gets progressively smaller.

Figure 35, which includes figures 35a, 35b, 35c, and 35d, shows in cross section the effect which the exactitude principle has on the smoothness of the resulting surface as well on the error variance. Note that the examples are produced in two-dimensional maps, but the method is formulated as a general 3D solution.

In figure 4, recall that a cross section 36 through a cubic volume of earth formation 34, which includes a plurality of random variables (scattered data samples) 44a, 44b, 44c, and 44d, can be mapped; that is, a map can be generated which represents that cross section 36, such as the maps discussed above with reference to figures 16, 18, 20-22, and 24-28.

Referring to figure 36, the cubic volume of earth formation 34 of figure 4 is illustrated again in figure 36. However, in figure 36, the cubic volume of earth formation 34 includes three cross sections (provided as an example for purposes of this discussion only): cross section 36a, cross section 36b, and cross section 36c. Each cross section 36a through 36c includes the intersection 54 of figures 9 and 10. In addition, each cross section 36a-36c includes the plurality of parameter values 44a through 44d. The above discussion with reference to figures 1 through 29 disclosed how a ‘corrected value’ is assigned to the intersection 54 and a unique color is assigned to that corrected value. For example, in figure 24, the corrected value

“(1-Pcu)[corrected]” was assigned to intersection 54 and a unique color was assigned thereto. Similarly, in figures 25, 26, 27, and 28, the corrected values “Xp(corrected)”, “lower limit(corrected)”, “spread(corrected)”, and “upper limit(corrected)” were assigned to intersection 54 and unique colors were assigned thereto. In figure 9, using the novel methods discussed above, other such ‘corrected values’ [i.e., (1-Pcu)[corrected], Xp(corrected), lower limit(corrected), spread(corrected), and upper limit(corrected)] are also assigned to all the other intersections, such as intersections 58 and 60 and 62, of the gridded cross section 52 of figure 9. As a result, in accordance with one aspect of the present invention, the maps of figures 33, 34, and 35 were generated.

However, since the cubic volume of earth 34 of figure 36 comprises a plurality time slices/horizons or cross sections 36a-36c, and since the novel methods of the present invention can generate a map for each such cross section, the novel methods discussed above which are practiced by the present invention can also be used to generate a cube 34, such as the cube 34 of figure 43. A method for generating a cube 34 is discussed below with reference to figures 37 through 43 of the drawings.

In figure 37, the novel methods discussed above for generating the ‘corrected values’ illustrated in figure 23 {i.e., ‘(1-Pcu)[corrected]’, ‘Xp(corrected)’, ‘lower limit(corrected)’, ‘spread(corrected)’, and ‘upper limit(corrected)’} are used to determine three ‘corrected values’ (i.e., corrected value A, corrected value B, and corrected value C) for assignment, respectively, to intersections 80, 82, and 84, as shown in figure 37.

In figure 38, the novel methods discussed above for generating the ‘corrected values’ are used to determine three additional ‘corrected values’ D, E, and F for assignment, respectively, to intersections 86, 88, and 90, as shown in figure 38.

In figure 39, the novel methods discussed above for generating the ‘corrected values’ are used to determine three additional ‘corrected values’ G, H, and I for assignment, respectively, to intersections 92, 94, and 96, as shown in figure 39.

In figure 40, the novel methods discussed above for generating the ‘corrected values’ are used to determine three additional ‘corrected values’ J, K, and L for assignment, respectively, to intersections 98, 100, and 102, as shown in figure 40.

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In figure 41, the novel methods discussed above for generating the ‘corrected values’ are used to determine three additional ‘corrected values’ M, N, and O for assignment, respectively, to intersections 104, 106, and 108, as shown in figure 41.

10 In figure 42, the novel methods discussed above for generating the ‘corrected values’ are used to determine three additional ‘corrected values’ P, Q, and R for assignment, respectively, to intersections 110, 112, and 114, as shown in figure 42.

15 In figure 43, when all the intersections on each cross section 36a, 36b, and 36c of the cube 34 have a ‘corrected value’ assigned thereto, the cube 34 of figure 43 will be generated. When unique colors are assigned to each such ‘corrected value’, a three dimensional (3D) cube, representing the cubic volume of earth 34 shown in figure 4, will be generated.

20 The invention being thus described, it will be obvious that the same may be varied in many ways. Such variations are not to be regarded as a departure from the spirit and scope of the invention, and all such modifications as would be obvious to one skilled in the art are intended to be included within the scope of the following claims.

I CLAIM:

1. A method of generating a map illustrating a set of characteristics of a cross section through an earth formation representing a time slice or a horizon through said

5 formation in response to a plurality of scattered data observations on said cross section representing a plurality of parameters located at a plurality of locations on said cross section, comprising the steps of:

10 (a) gridding said cross section thereby generating a gridded cross section which includes a grid having a plurality of intersections and said plurality of scattered data observations distributed among the intersections of said grid on said cross section;

15 (b) obtaining a unique cumulative distribution function associated with each intersection of the grid of the gridded cross section thereby producing a plurality of cumulative distribution functions associated, respectively, with the plurality of intersections of said grid;

20 (c) choosing a value from each of the cumulative distribution function at each of the intersections of the gridded cross section thereby producing a plurality of values associated, respectively, with the plurality of intersections, and

(d) assigning each value to its associated intersection of the gridded cross section and assigning a unique color to said each value thereby generating a map illustrating said set of characteristics of said cross section through said earth formation.

2. The method of claim 1, wherein the obtaining step (b), for obtaining a unique cumulative distribution function associated with each intersection of the gridded cross-section, comprises the steps of:

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(b1) Kriging the gridded cross section thereby generating a plurality of expected values and a plurality of corresponding standard deviations associated, respectively, with the plurality of intersections of the grid of the gridded cross section;

10 (b2) producing a probability density function associated with each expected value and each corresponding standard deviation generated from step (b1) thereby producing a plurality of probability density functions corresponding, respectively, to the plurality of intersections of the grid of the gridded cross section; and

15 (b3) producing a cumulative distribution function associated with each probability density function produced from step (b2) thereby producing a plurality of cumulative distribution functions corresponding, respectively, to the plurality of probability density functions which correspond, respectively, to the plurality of intersections of the grid of the gridded cross section.

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3. The method of claim 2, wherein the choosing step (c), for choosing a value from each of the cumulative distribution functions at each of the intersections of the gridded cross section, comprises the steps of:

25 (c1) choosing a probability “(1-Pcu)” from each of the cumulative distribution functions.

4. The method of claim 2, wherein the choosing step (c), for choosing a value from each of the cumulative distribution functions at each of the intersections of the gridded cross section, comprises the steps of:

5

(c1) choosing a cutoff “Xp” from each of the cumulative distribution functions.

5. The method of claim 2, wherein the choosing step (c), for choosing a value from each of the cumulative distribution functions at each of the intersections of the gridded cross section, comprises the steps of:

10

(c1) choosing a lower limit from each of the cumulative distribution functions.

6. The method of claim 2, wherein the choosing step (c), for choosing a value from each of the cumulative distribution functions at each of the intersections of the gridded cross section, comprises the steps of:

15

(c1) choosing an upper limit from each of the cumulative distribution functions.

7. The method of claim 2, wherein the choosing step (c), for choosing a value from each of the cumulative distribution functions at each of the intersections of the gridded cross section, comprises the steps of:

20

(c1) choosing a spread from each of the cumulative distribution functions.

8. The method of claim 2, wherein the choosing step (c), for choosing a value from each of the cumulative distribution functions at each of the intersections of the gridded cross section, comprises the steps of:

5

(c1) applying an affine correction to each of the values chosen from each of the cumulative distribution functions associated with each of the intersections of the gridded cross section thereby choosing a plurality of corrected values corresponding, respectively, to the plurality of intersections of the gridded cross section.

10

9. The method of claim 8, wherein the assigning step (d), for assigning each value to its associated intersection of the gridded cross section and assigning a unique color to said each value thereby generating said map, comprises the steps of:

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(d1) assigning each of said plurality of corrected values to its associated intersection of the gridded cross section and assigning said unique color to each said corrected value thereby generating said map illustrating said set of characteristics of said cross section through said earth formation.

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10. The method of claim 9, wherein said corrected value is a probability “(1-P_{cu})”.

11. The method of claim 9, wherein said corrected value is a cutoff “X_p”.

12. The method of claim 9, wherein said corrected value is a lower limit.

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13. The method of claim 9, wherein said corrected value is an upper limit.

14. The method of claim 9, wherein said corrected value is a spread.

15. A program storage device readable by a machine, tangibly embodying a program of instructions executable by the machine to perform method steps for generating a map illustrating a set of characteristics of a cross section through an earth formation
- 5 representing a time slice or a horizon through said formation in response to a plurality of scattered data observations on said cross section representing a plurality of parameters located at a plurality of locations on said cross section, said method steps comprising the steps of:
- 10 (a) gridding said cross section thereby generating a gridded cross section which includes a grid having a plurality of intersections and said plurality of scattered data observations distributed among the intersections of said grid on said cross section;
- 15 (b) obtaining a unique cumulative distribution function associated with each intersection of the grid of the gridded cross section thereby producing a plurality of cumulative distribution functions associated, respectively, with the plurality of intersections of said grid;
- 20 (c) choosing a value from each of the cumulative distribution function at each of the intersections of the gridded cross section thereby producing a plurality of values associated, respectively, with the plurality of intersections, and
- 25 (d) assigning each value to its associated intersection of the gridded cross section and assigning a unique color to said each value thereby generating a map illustrating said set of characteristics of said cross section through said earth formation.

16. The program storage device of claim 15, wherein the obtaining step (b), for obtaining a unique cumulative distribution function associated with each intersection of the gridded cross-section, comprises the steps of:

5

(b1) Kriging the gridded cross section thereby generating a plurality of expected values and a plurality of corresponding standard deviations associated, respectively, with the plurality of intersections of the grid of the gridded cross section;

10 (b2) producing a probability density function associated with each expected value and each corresponding standard deviation generated from step (b1) thereby producing a plurality of probability density functions corresponding, respectively, to the plurality of intersections of the grid of the gridded cross section; and

15 (b3) producing a cumulative distribution function associated with each probability density function produced from step (b2) thereby producing a plurality of cumulative distribution functions corresponding, respectively, to the plurality of probability density functions which correspond, respectively, to the plurality of intersections of the grid of the gridded cross section.

20

17. The program storage device of claim 16, wherein the choosing step (c), for choosing a value from each of the cumulative distribution functions at each of the intersections of the gridded cross section, comprises the steps of:

25 (c1) choosing a probability “(1-Pcu)” from each of the cumulative distribution functions.

18. The program storage device of claim 16, wherein the choosing step (c), for choosing a value from each of the cumulative distribution functions at each of the intersections of the gridded cross section, comprises the steps of:

5

(c1) choosing a cutoff “Xp” from each of the cumulative distribution functions.

19. The program storage device of claim 16, wherein the choosing step (c), for choosing a value from each of the cumulative distribution functions at each of the intersections of the gridded cross section, comprises the steps of:

10

(c1) choosing a lower limit from each of the cumulative distribution functions.

20. The program storage device of claim 16, wherein the choosing step (c), for choosing a value from each of the cumulative distribution functions at each of the intersections of the gridded cross section, comprises the steps of:

15

(c1) choosing an upper limit from each of the cumulative distribution functions.

21. The program storage device of claim 16, wherein the choosing step (c), for choosing a value from each of the cumulative distribution functions at each of the intersections of the gridded cross section, comprises the steps of:

20

(c1) choosing a spread from each of the cumulative distribution functions.

22. The program storage device of claim 16, wherein the choosing step (c), for choosing a value from each of the cumulative distribution functions at each of the intersections of the gridded cross section, comprises the steps of:

5

(c1) applying an affine correction to each of the values chosen from each of the cumulative distribution functions associated with each of the intersections of the gridded cross section thereby choosing a plurality of corrected values corresponding, respectively, to the plurality of intersections of the gridded cross section.

10

23. The program storage device of claim 22, wherein the assigning step (d), for assigning each value to its associated intersection of the gridded cross section and assigning a unique color to said each value thereby generating said map, comprises the steps of:

15

(d1) assigning each of said plurality of corrected values to its associated intersection of the gridded cross section and assigning said unique color to each said corrected value thereby generating said map illustrating said set of characteristics of said cross section through said earth formation.

20

24. The program storage device of claim 23, wherein said corrected value is selected from a group consisting of: a probability “(1-P_{cu})”, a cutoff “X_p”, a lower limit, an upper limit, and a spread.

25. An apparatus adapted for generating a map representing a cross section through an earth formation in response to a plurality of scattered observation data distributed throughout said cross section, said cross section representing a time slice or horizon through said formation, comprising:

first apparatus adapted for gridding said cross section thereby generating a first gridded cross section which includes a plurality of intersections and said plurality of scattered observation data distributed throughout said cross section;

second apparatus responsive to said first gridded cross section adapted for Kriging said first gridded cross section thereby generating a second gridded cross section having a plurality of intersections wherein each intersection of said second gridded cross section includes an expected value of a parameter and a standard deviation;

third apparatus responsive to said second gridded cross section for generating a plurality of cumulative distribution functions associated, respectively, with said plurality of intersections of said second gridded cross section; and

fourth apparatus adapted for selecting a plurality of values, respectively, from said plurality of cumulative distribution functions and for assigning said plurality of values and a plurality of unique colors to the respective plurality of intersections of said second gridded cross section thereby generating said map.

26. The apparatus of claim 25, wherein said third apparatus, for generating said plurality of cumulative distribution functions associated, respectively, with said plurality of intersections of said second gridded cross section, comprises:

5

probability density function generation apparatus adapted for generating a plurality of probability density functions associated, respectively, with said plurality of intersections of said second gridded cross section in response to the plurality of expected values and the plurality of standard deviations associated, respectively, with said plurality of intersections of said second gridded cross section;

10

cumulative distribution function generation apparatus responsive to said plurality of probability density functions adapted for generating said plurality of cumulative distribution functions from said plurality of probability density functions which are associated, respectively, with said plurality of intersections of said second gridded cross section.

15

27. The apparatus of claim 26, wherein each of said plurality of values selected, respectively, by said fourth apparatus from said plurality of cumulative distribution functions, is selected from a group consisting of: a probability “(1-Pcu)”, a cutoff “Xp”, a lower limit, an upper limit, and a spread.

20

28. The apparatus of claim 26, wherein said fourth apparatus, adapted for selecting said plurality of values, respectively, from said plurality of cumulative distribution functions and for assigning said plurality of values and said plurality of unique colors to the respective plurality of intersections of said second gridded cross section, comprises:

25

correction apparatus adapted for applying an affine correction to each of said plurality of values selected, respectively, from said plurality of cumulative distribution functions thereby generating a plurality of corrected values corresponding,
5 respectively, to said plurality of intersections of said second gridded cross section;
and

assignment apparatus adapted for assigning said plurality of corrected values and a plurality of unique colors to the respective plurality of intersections of said second
10 gridded cross section thereby generating said map.

29. The apparatus of claim 28, wherein each of said plurality of corrected values generated by said correction apparatus is selected from a group consisting of: a corrected probability “ $(1-P_{cu})[\text{corrected}]$ ”, a corrected cutoff “ $X_p(\text{corrected})$ ”, a
15 corrected lower limit “lower limit (corrected)”, a corrected upper limit “upper limit (corrected)”, and a corrected spread “spread (corrected)”.

30. A method of generating a cube illustrating a set of characteristics of an earth formation disposed within a cubic volume of earth, said cube including a plurality of
20 cross sections, each cross section including a plurality of scattered data samples, each cross section being gridded and including a plurality of intersections, comprising the steps of:

(a) determining a plurality of cumulative distribution functions corresponding,
25 respectively, to the plurality of intersections for each of said plurality of cross sections;

(b) selecting a value from each of said cumulative distribution functions thereby selecting a plurality of values corresponding, respectively, to said plurality of
30 cumulative distribution functions for each of said plurality of cross sections;

(c) assigning said plurality of values, respectively, to said plurality of intersections for each of said plurality of cross sections; and

5 (d) assigning a plurality of unique colors, respectively, to said plurality of values assigned, respectively, to said plurality of intersections.

31. The method of claim 30, wherein the assigning step (c) comprises the steps of:

10 (c1) correcting each of the values selected from said cumulative distribution functions during the selecting step (b) thereby generating a plurality of corrected values; and

(c2) assigning said plurality of corrected values, respectively, to said plurality of intersections for each of said plurality of cross sections.

15 32. The method of claim 31, wherein the assigning step (d) comprises the steps of:

(d1) assigning a plurality of unique colors, respectively, to said plurality of corrected values assigned, respectively, to said plurality of intersections.

20 33. The method of claim 30, wherein the determining step (a), for determining a plurality of cumulative distribution functions, comprises the steps of:

25 (a1) determining a plurality of expected values and a plurality of standard deviations corresponding, respectively, to the plurality of intersections for each of said plurality of cross sections, an expected value and a standard deviation being associated with each intersection;

30 (a2) determining a plurality of probability density functions corresponding, respectively, to said plurality of expected values and said plurality of standard deviations for each of said plurality of cross sections, a probability density function being associated with each intersection; and

(a3) determining a plurality of cumulative distribution functions corresponding, respectively, to said plurality of probability density functions for each of said plurality of cross sections.

5

34. The method of claim 33, wherein each of the values, selected from each of said cumulative distribution functions during the selecting step (b), is selected from a group consisting of: a probability “(1-Pcu)”, a cutoff “Xp”, a lower limit, an upper limit, and a spread.

10

35. The method of claim 34, wherein the plurality of corrected values generated during the correcting step (c1) is selected from a group consisting of: a corrected probability “(1-Pcu)[corrected]”, a corrected cutoff “Xp(corrected)”, a corrected lower limit “lower limit (corrected)”, a corrected upper limit

15 “upper limit (corrected)”, and a corrected spread “spread (corrected)”.

36. A program storage device readable by a machine, tangibly embodying a program of instructions executable by the machine to perform method steps for generating a cube illustrating a set of characteristics of an earth formation disposed within a cubic volume of earth, said cube including a plurality of cross sections, each cross section including a plurality of scattered data samples, each cross section being gridded and including a plurality of intersections, said method steps comprising the steps of:

20

(a) determining a plurality of cumulative distribution functions corresponding, respectively, to the plurality of intersections for each of said plurality of cross sections;

25

(b) selecting a value from each of said cumulative distribution functions thereby selecting a plurality of values corresponding, respectively, to said plurality of cumulative distribution functions for each of said plurality of cross sections;

30

(c) assigning said plurality of values, respectively, to said plurality of intersections for each of said plurality of cross sections; and

5 (d) assigning a plurality of unique colors, respectively, to said plurality of values assigned, respectively, to said plurality of intersections.

37. The program storage device of claim 36, wherein the assigning step (c) comprises the steps of:

10 (c1) correcting each of the values selected from said cumulative distribution functions during the selecting step (b) thereby generating a plurality of corrected values; and

(c2) assigning said plurality of corrected values, respectively, to said plurality of intersections for each of said plurality of cross sections.

15

38. The program storage device of claim 37, wherein the assigning step (d) comprises the steps of:

(d1) assigning a plurality of unique colors, respectively, to said plurality of corrected
20 values assigned, respectively, to said plurality of intersections.

39. The program storage device of claim 38, wherein the determining step (a), for determining a plurality of cumulative distribution functions, comprises the steps of:

25 (a1) determining a plurality of expected values and a plurality of standard deviations corresponding, respectively, to the plurality of intersections for each of said plurality of cross sections, an expected value and a standard deviation being associated with each intersection;

(a2) determining a plurality of probability density functions corresponding, respectively, to said plurality of expected values and said plurality of standard deviations for each of said plurality of cross sections, a probability density function being associated with each intersection; and

(a3) determining a plurality of cumulative distribution functions corresponding, respectively, to said plurality of probability density functions for each of said plurality of cross sections.

40. The program storage device of claim 39, wherein each of the values, selected from each of said cumulative distribution functions during the selecting step (b), is selected from a group consisting of: a probability “(1-Pcu)”, a cutoff “Xp”, a lower limit, an upper limit, and a spread.

41. The program storage device of claim 40, wherein the plurality of corrected values generated during the correcting step (c1) is selected from a group consisting of: a corrected probability “(1-Pcu)[corrected]”, a corrected cutoff “Xp(corrected)”, a corrected lower limit “lower limit (corrected)”, a corrected upper limit “upper limit (corrected)”, and a corrected spread “spread (corrected)”.

ABSTRACT OF THE DISCLOSURE

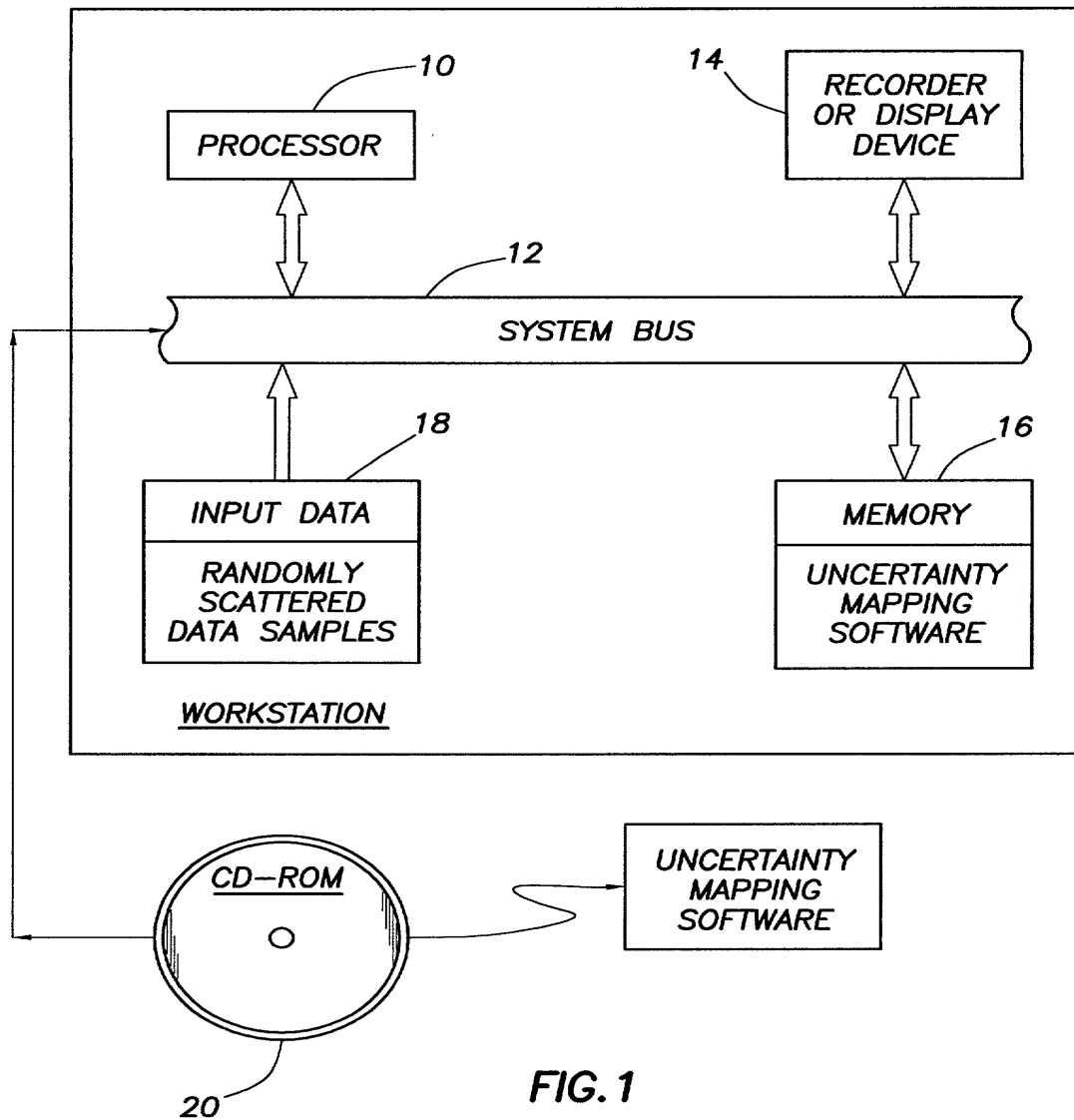
A new method is presented for generating a probability map, a cutoff map, and a

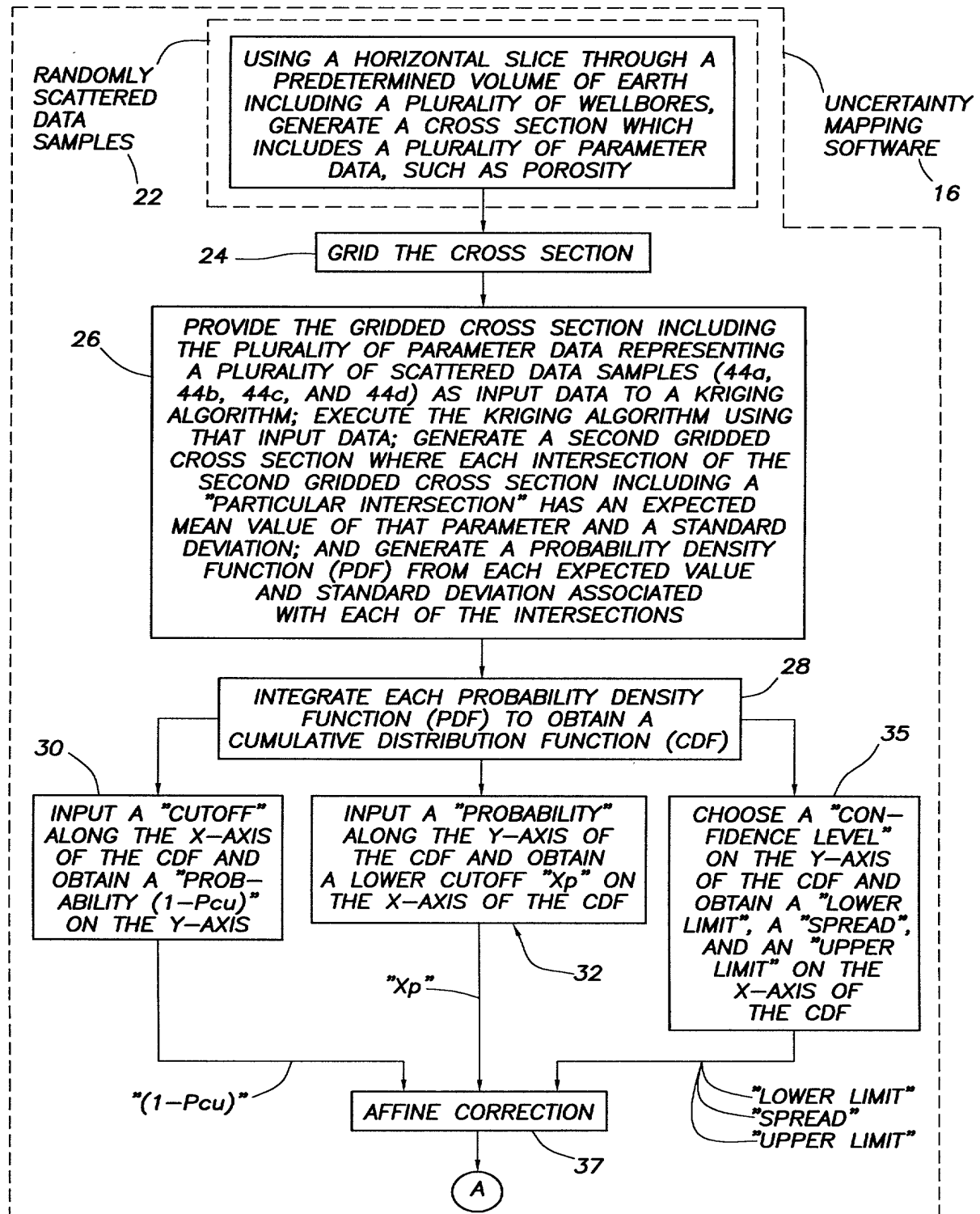
5 confidence limit map in one single operation. In addition, the new method can also generate a cube representing a cubic volume of earth formation by using the same method for generating the aforementioned maps. This is accomplished by:

(a) gridding a cross section, (b) Kriging the gridded cross section thereby producing a plurality of expected values and a corresponding plurality of standard deviations

10 associated, respectively, with the plurality of intersections on the gridded cross section, (c) generating a plurality of probability density functions which correspond, respectively, to the plurality of expected values/standard deviations of the plurality of intersections, (d) integrating each of the probability density functions thereby generating a plurality of cumulative distribution functions which correspond,

15 respectively, to the plurality of probability density functions, (e) choosing a value from each of the cumulative distribution functions associated with each of the intersections of the gridded cross section, and (f) assigning such value to its associated intersection of the gridded cross section and assigning a unique color to each such value, thereby generating a map illustrating the characteristics of the cross
20 section through the earth formation. Since a cube includes a plurality of gridded cross sections, by generating a map for each cross section, the new method will generate the cube.





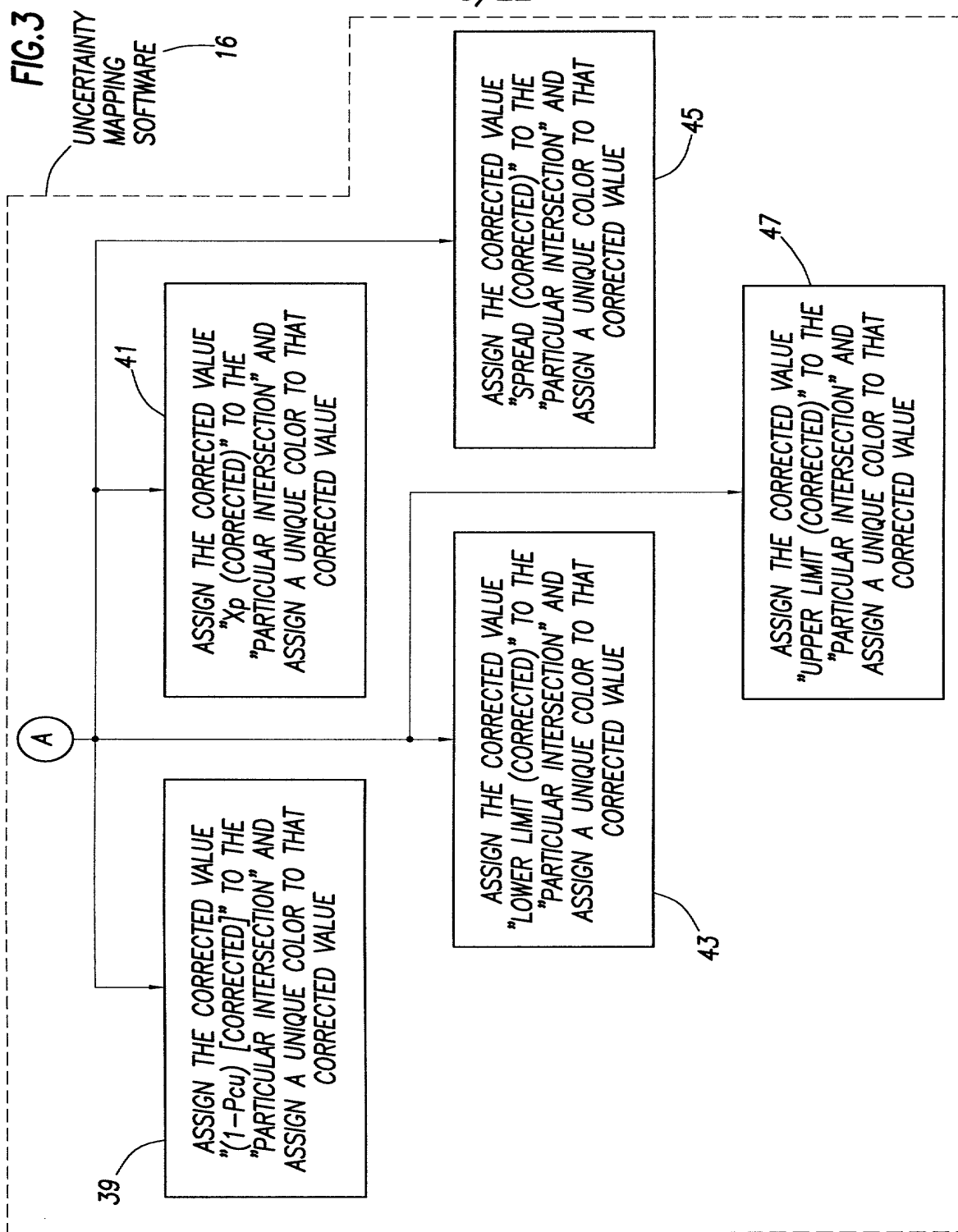


FIG. 4

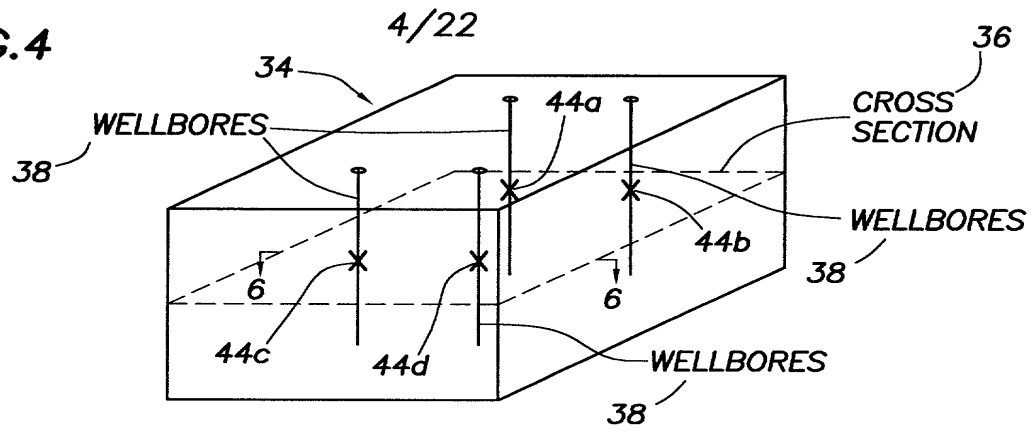


FIG. 5

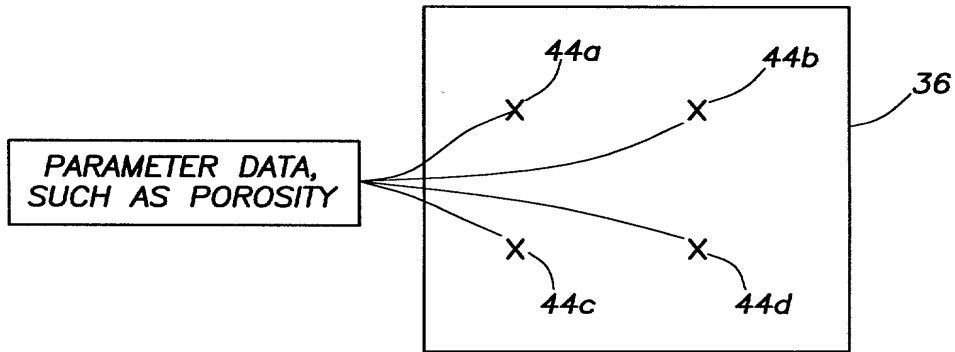
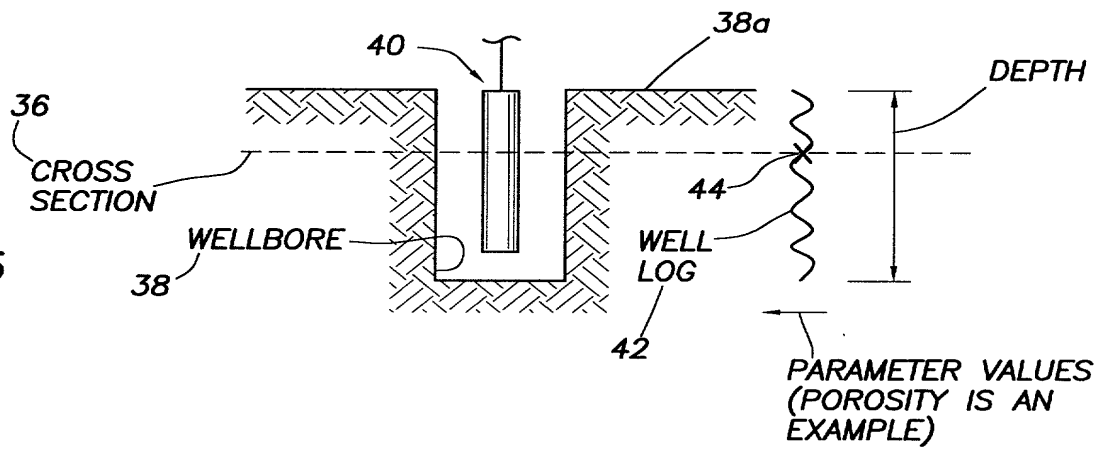
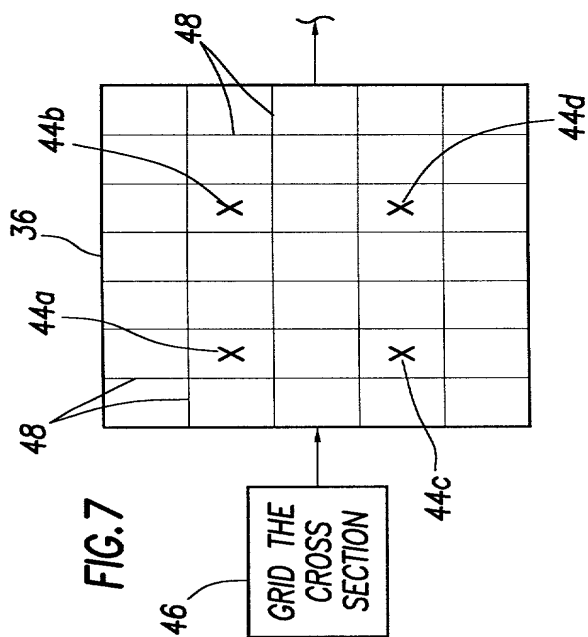


FIG. 6

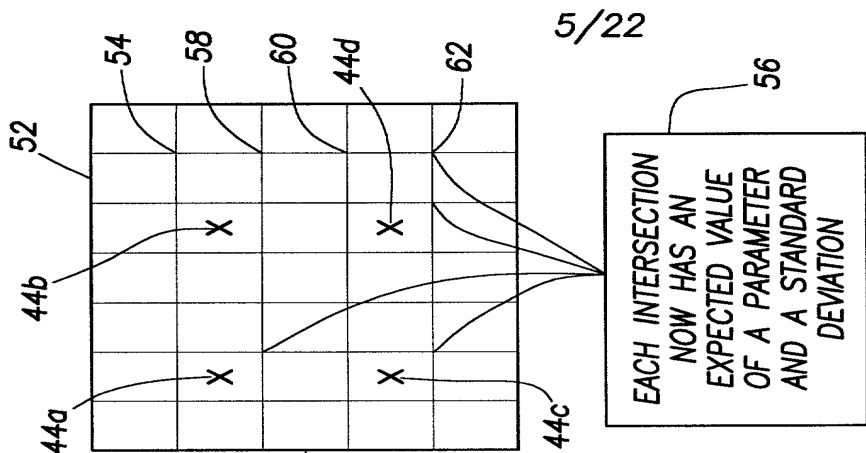
+



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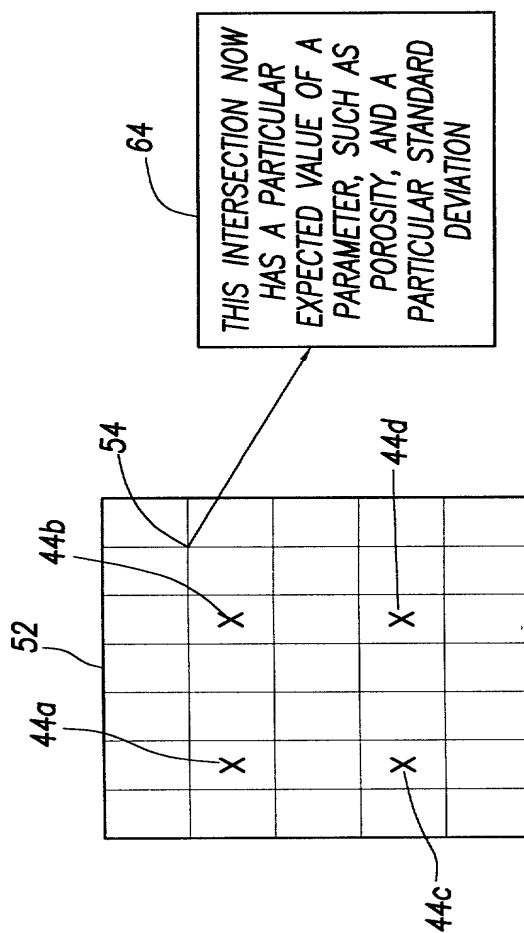
KRIGING ALGORITHM

FIG. 8



EACH INTERSECTION
NOW HAS AN
EXPECTED VALUE
OF A PARAMETER
AND A STANDARD
DEVIATION

FIG. 9



THIS INTERSECTION NOW
HAS A PARTICULAR
EXPECTED VALUE OF A
PARAMETER, SUCH AS
POROSITY, AND A
PARTICULAR STANDARD
DEVIATION

FIG. 10

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FIG. 10a

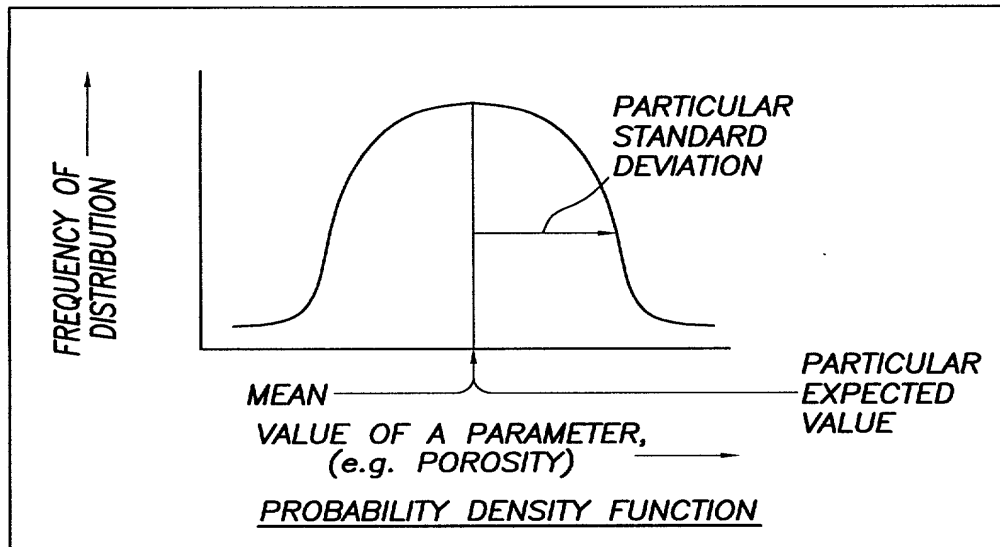


FIG. 11

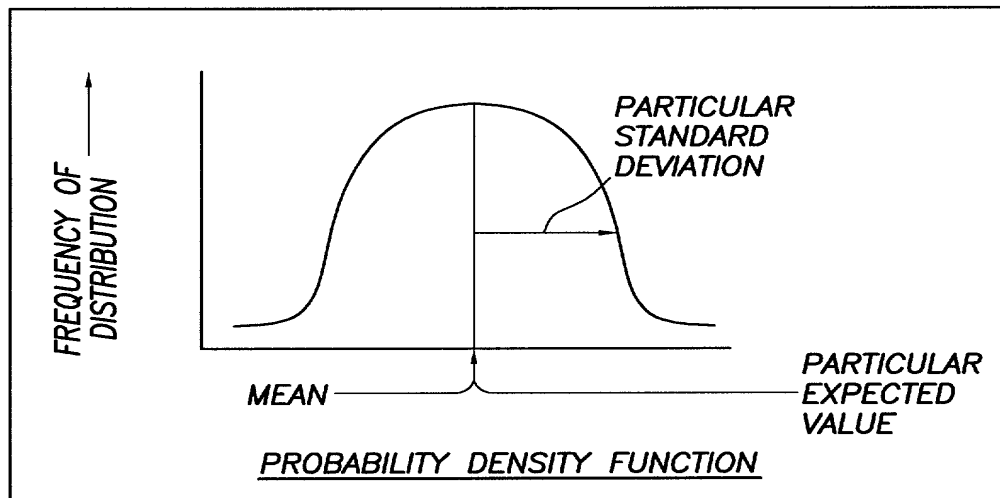


FIG. 12

INTEGRATE THE PROBABILITY DENSITY FUNCTION (PDF)
TO GET THE CUMULATIVE DISTRIBUTION FUNCTION (CDF)

66

+

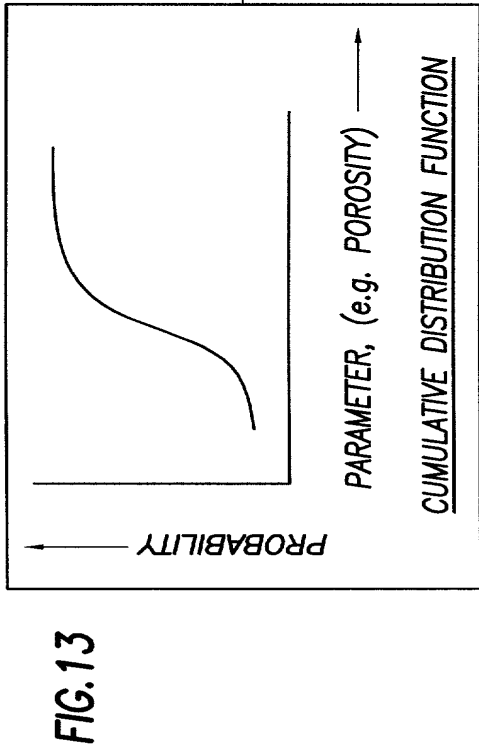


FIG. 14

68

USER INPUTS A "CUTOFF" X_p ALONG THE X-AXIS OF THE CDF (e.g. 10%) AND OBTAINS A PROBABILITY " P_{cu} " ON THE Y-AXIS

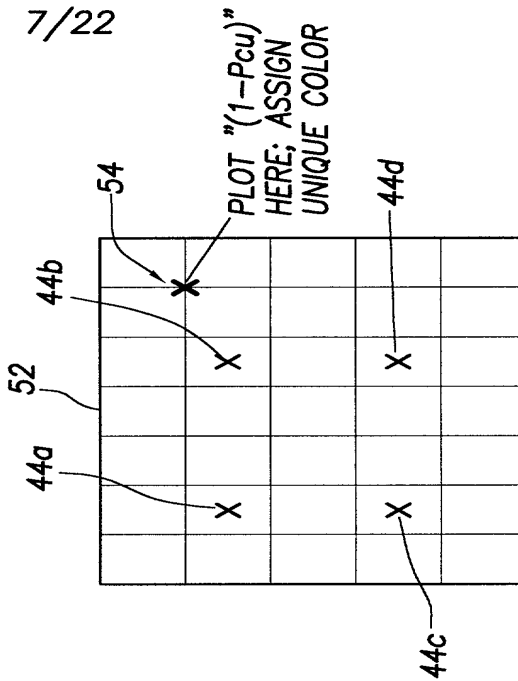
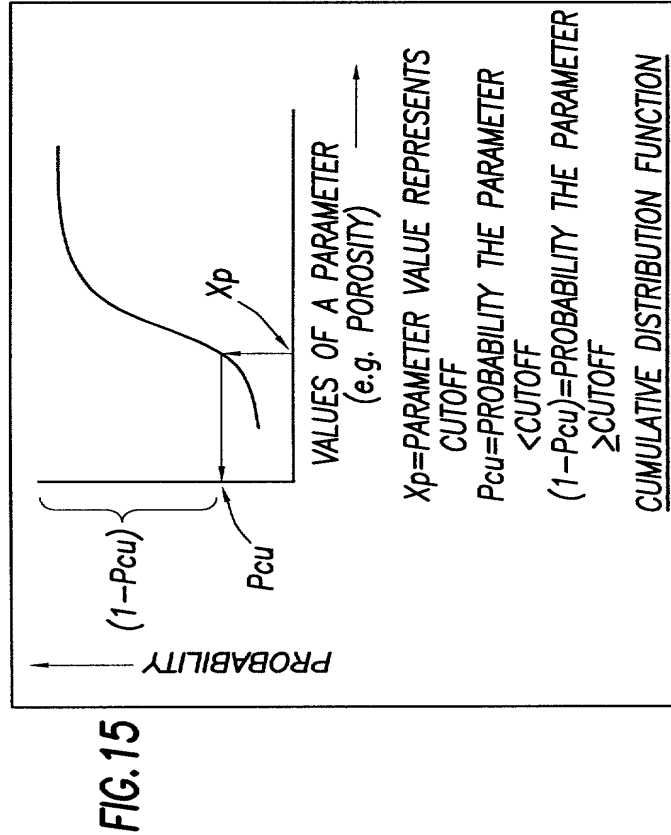


FIG. 16

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FIG.21

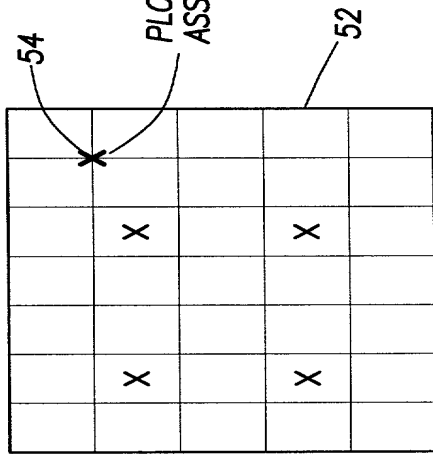
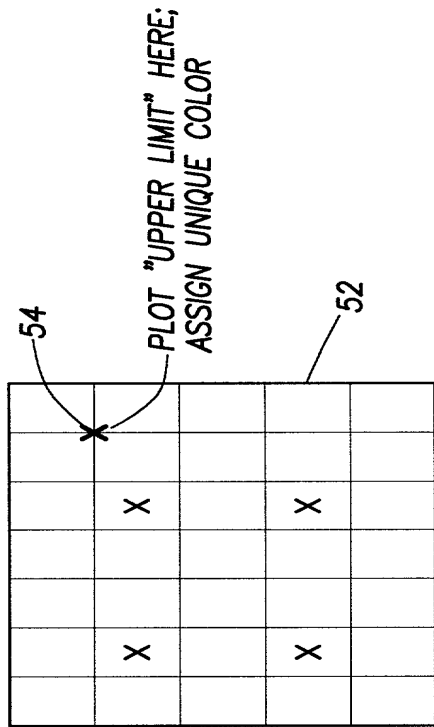


FIG.22



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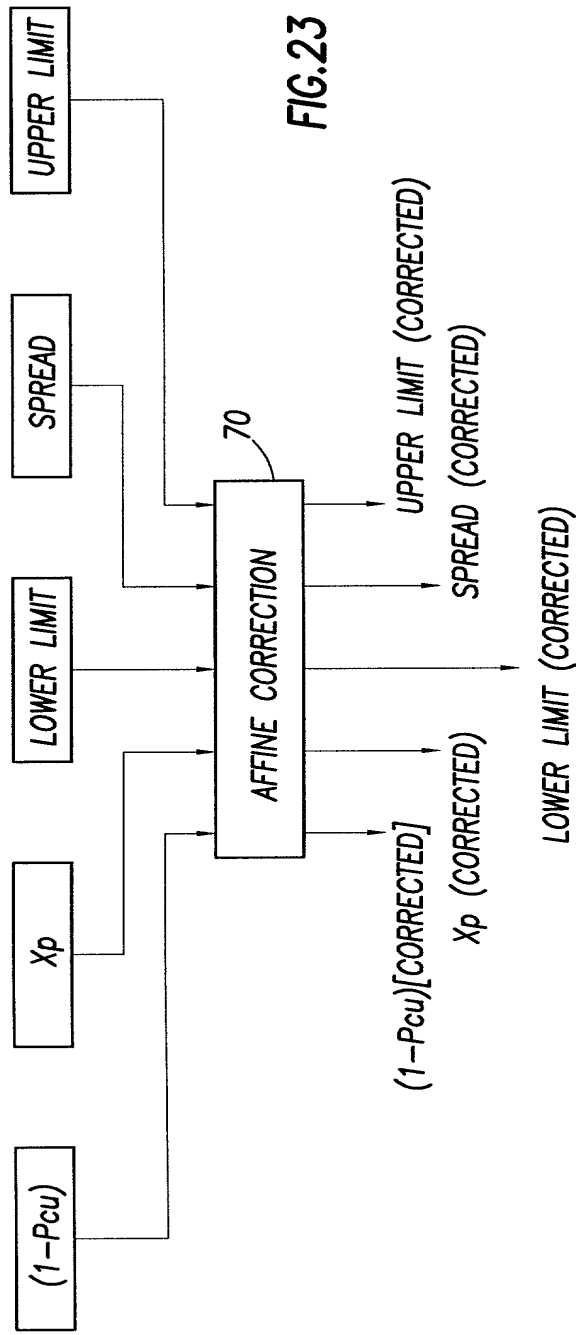
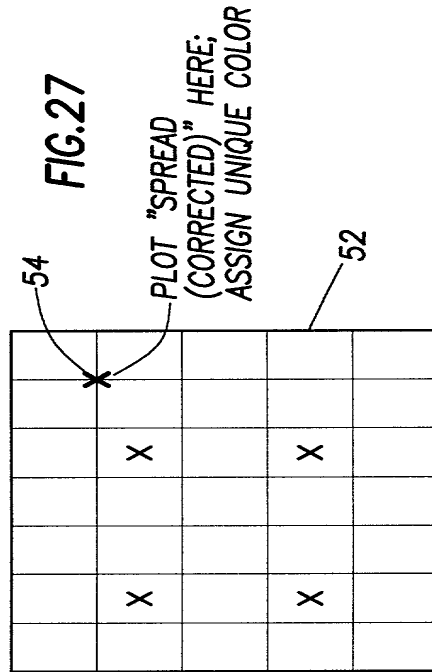
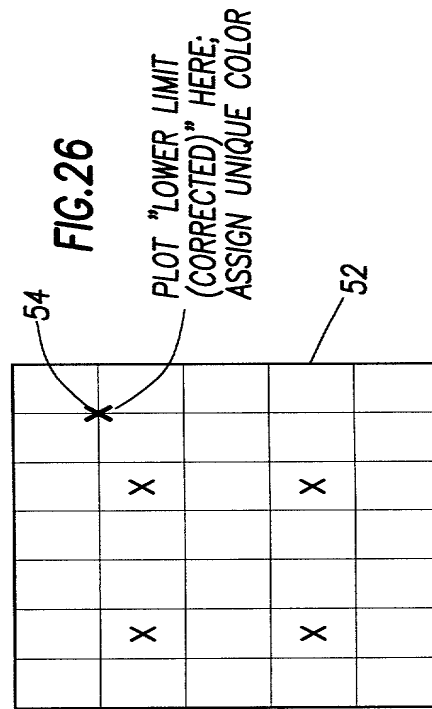
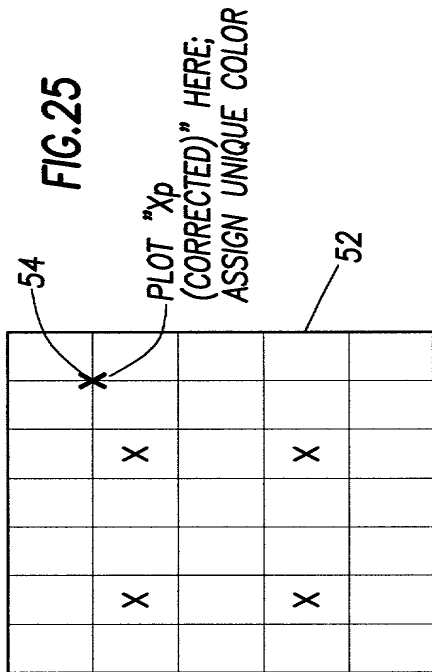
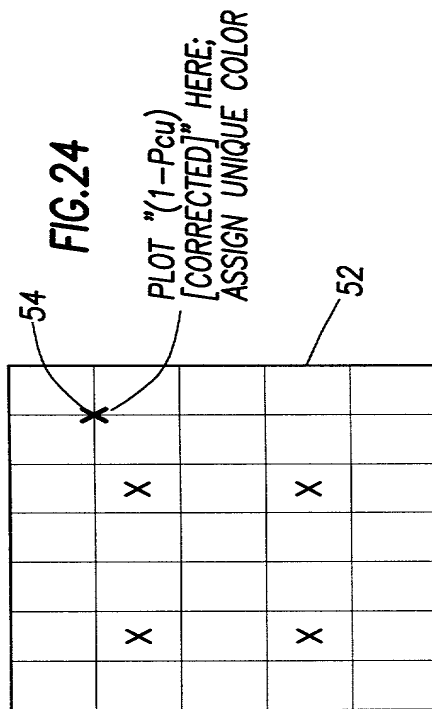


FIG.23

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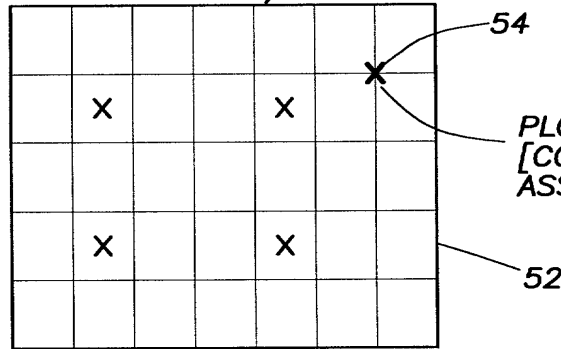


FIG.28

PLOT "UPPER LIMIT
[CORRECTED]" HERE;
ASSIGN UNIQUE COLOR

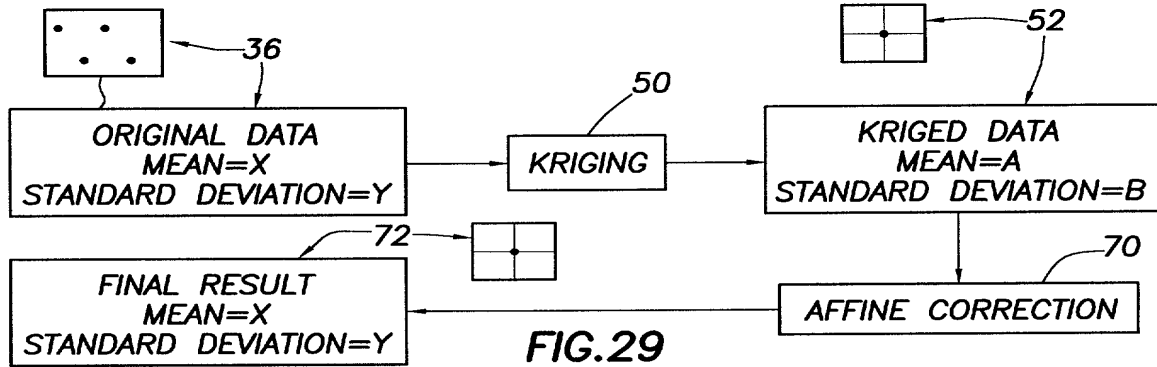
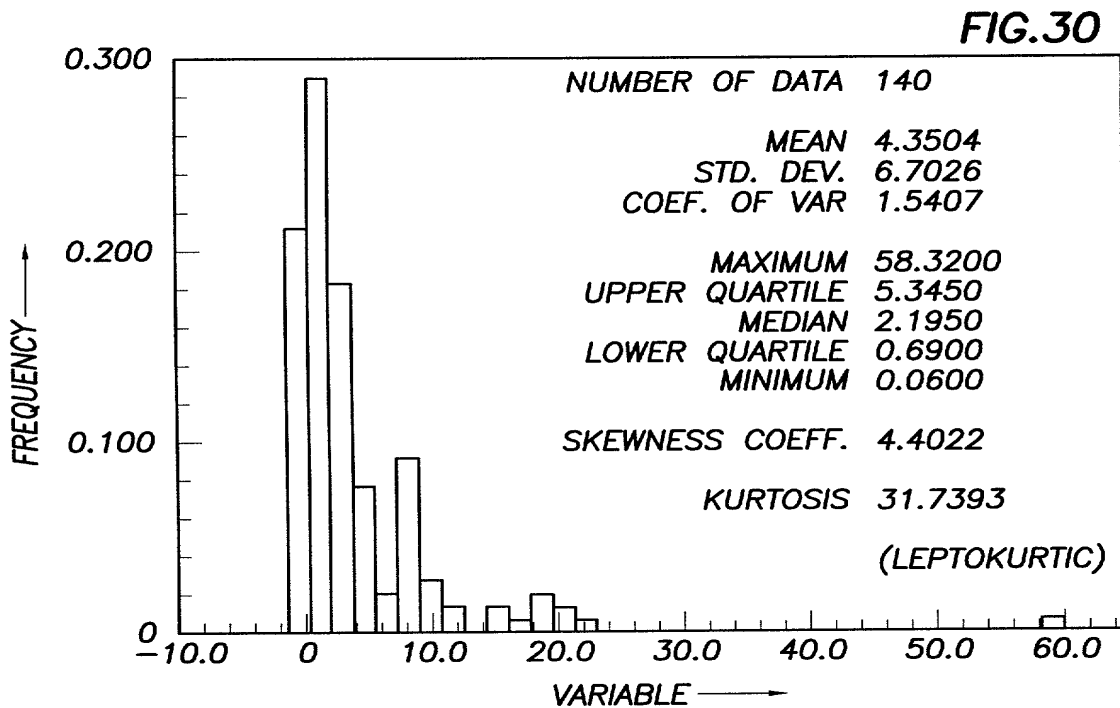


FIG.29



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FIG.31

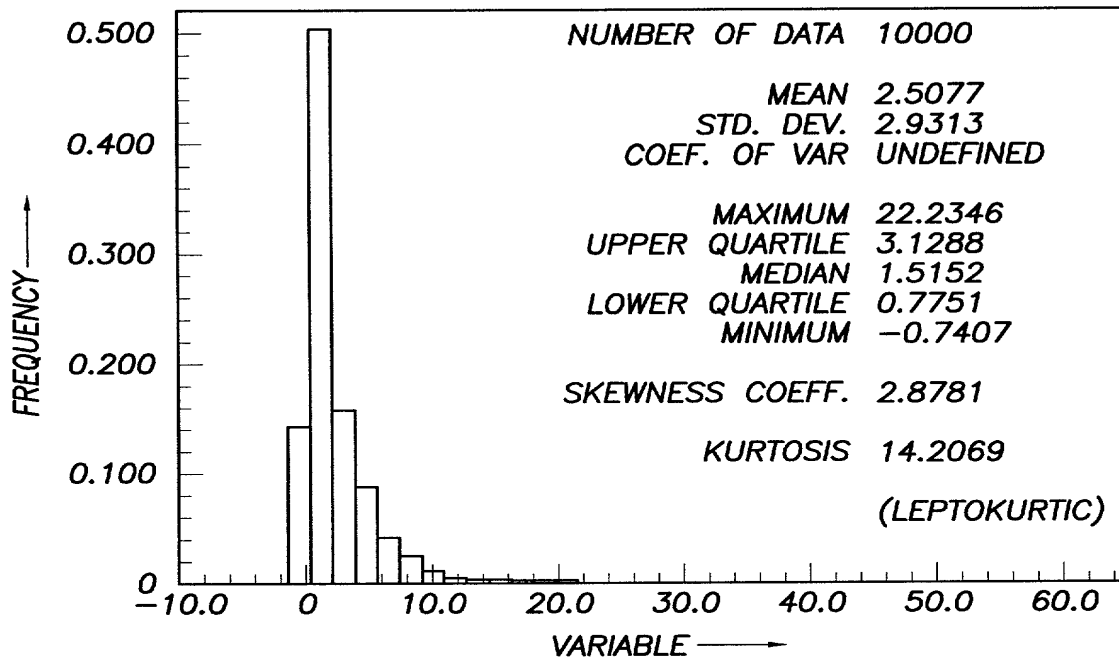


FIG.32

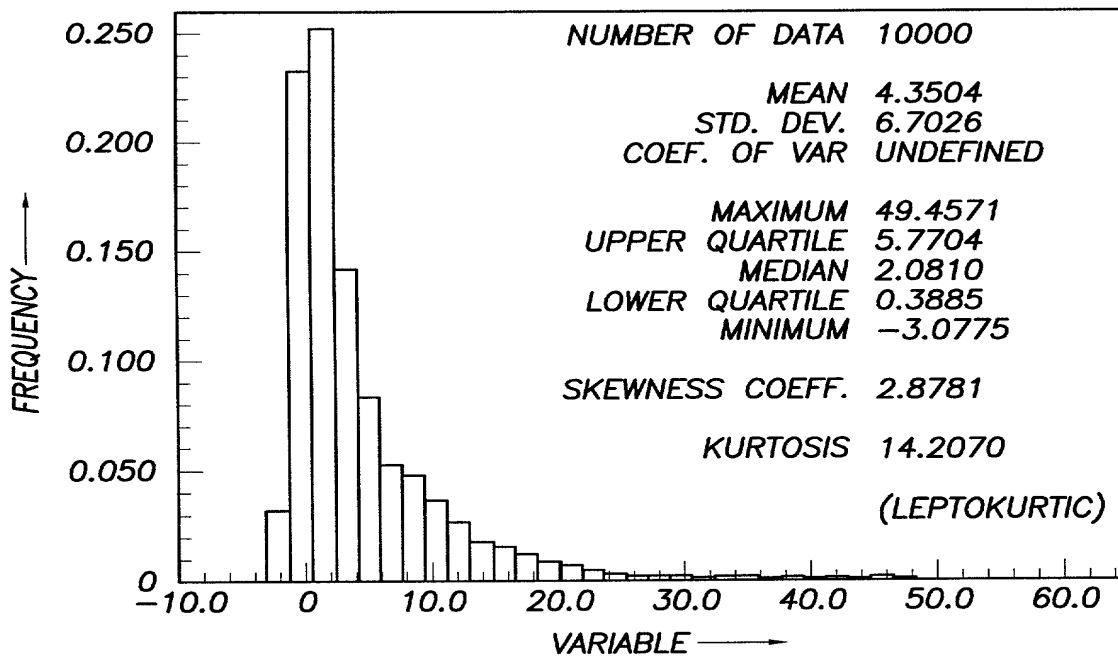


FIG.33

FIG.33a	FIG.33b
FIG.33c	FIG.33d

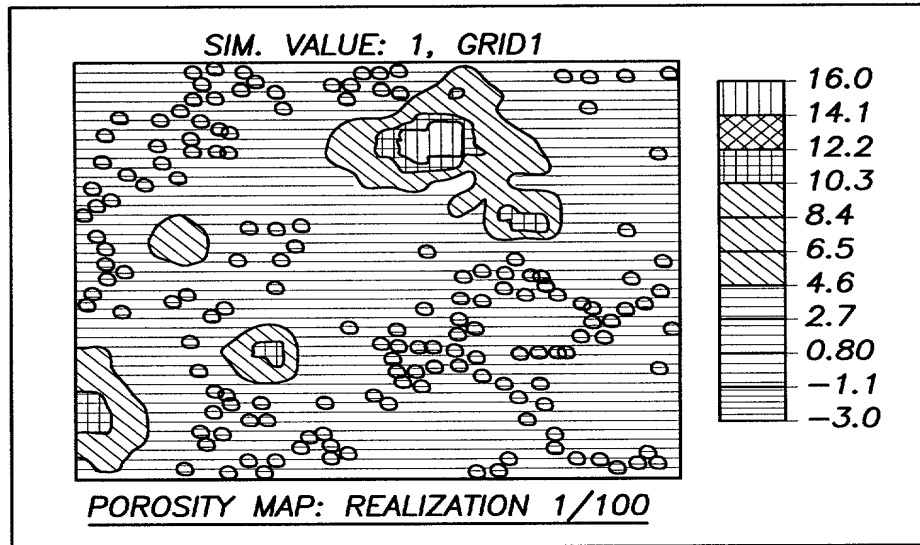
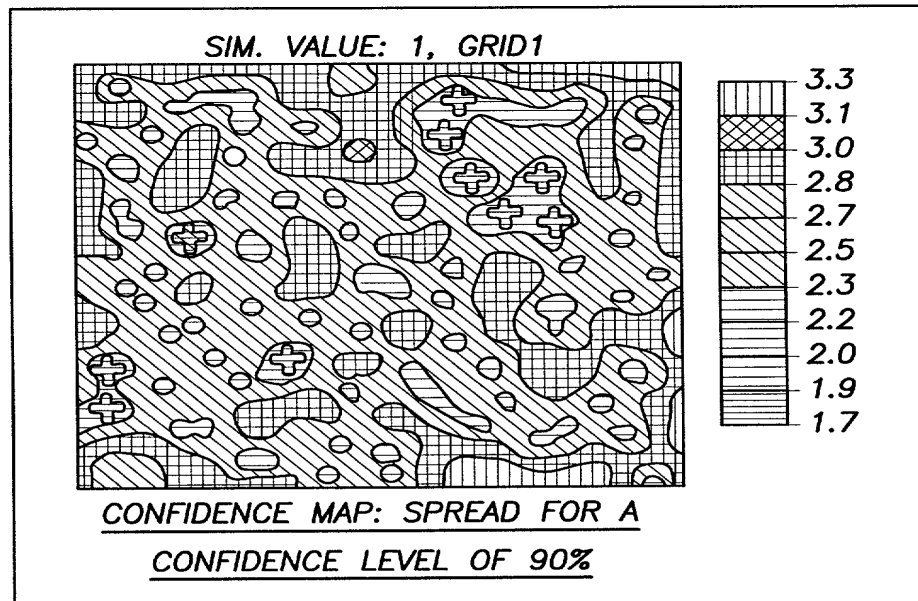
FIG.33a**FIG.33b**

FIG.33c

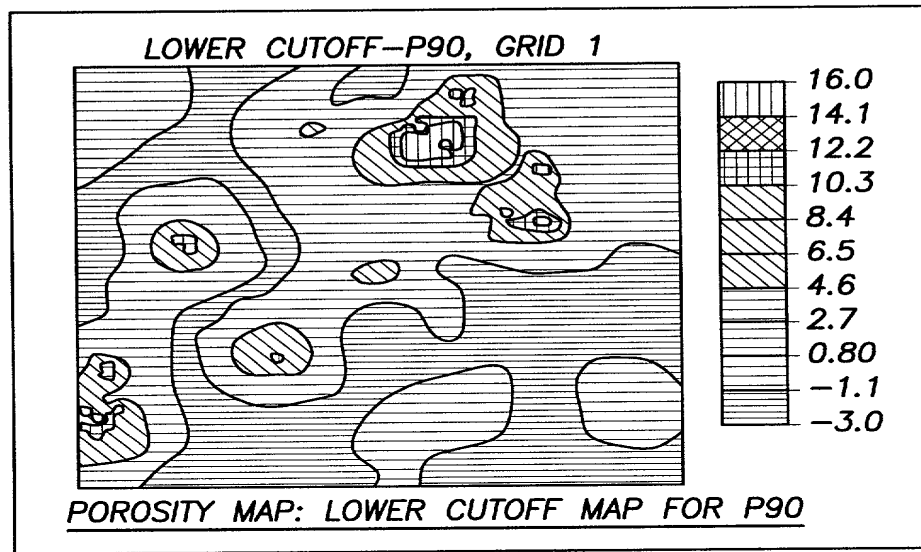


FIG.33d

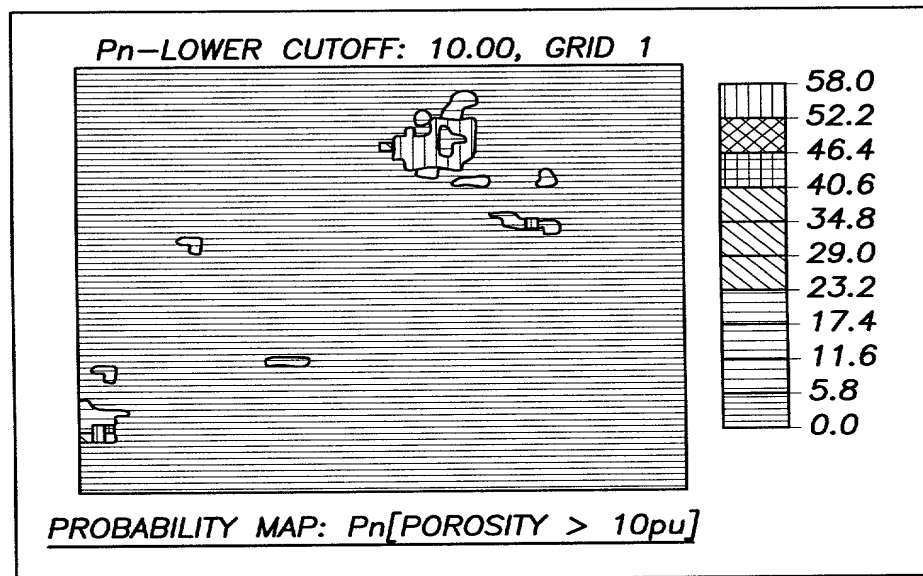


FIG.34

FIG.34a	FIG.34b
FIG.34c	FIG.34d

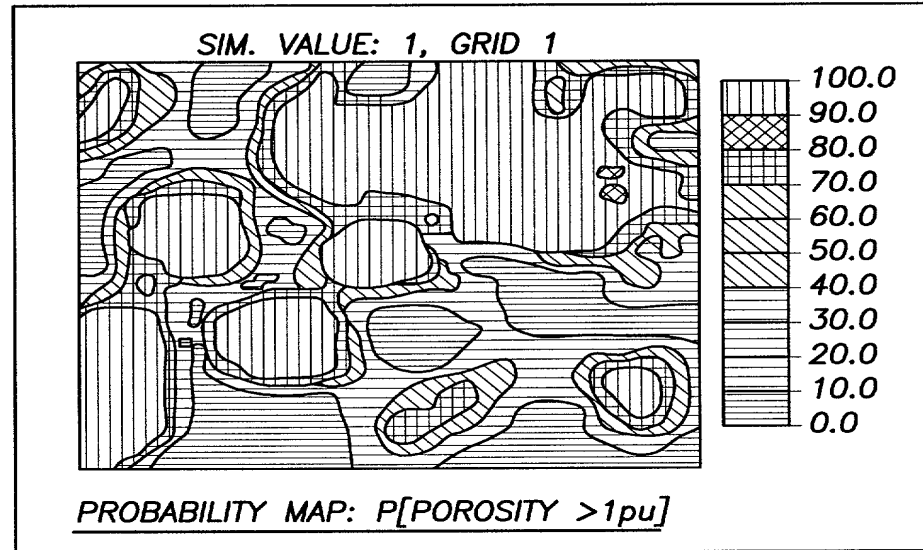
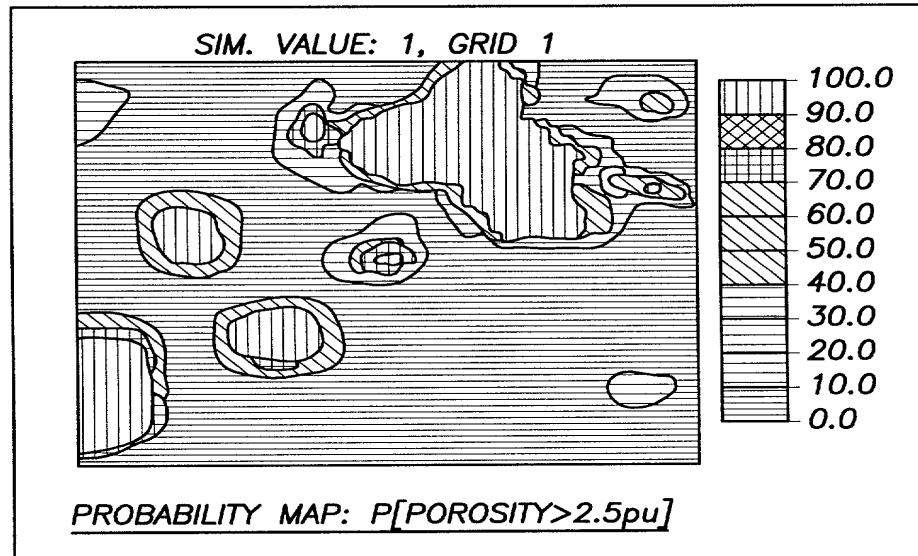
FIG.34a**FIG.34b**

FIG.34c

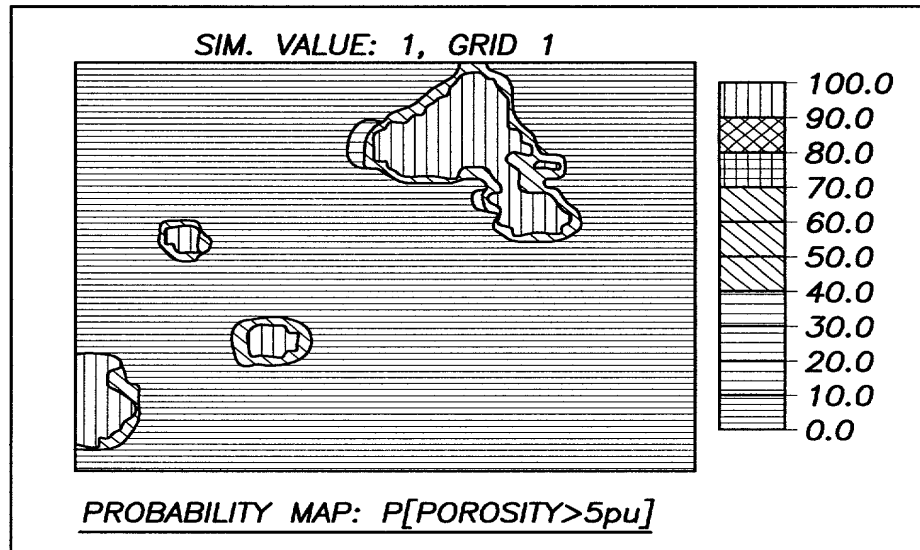
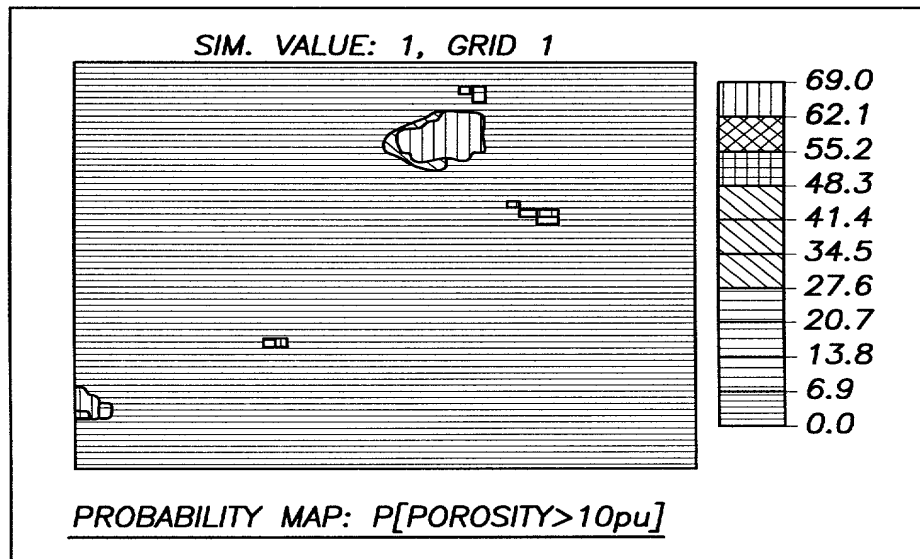


FIG.34d



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FIG.35

FIG.35a	FIG.35b
FIG.35c	FIG.35d

FIG.35a

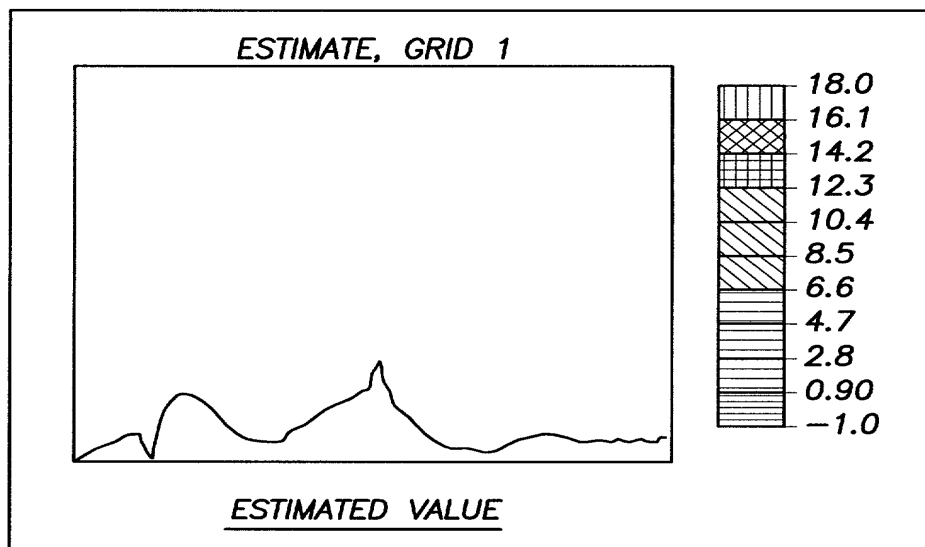
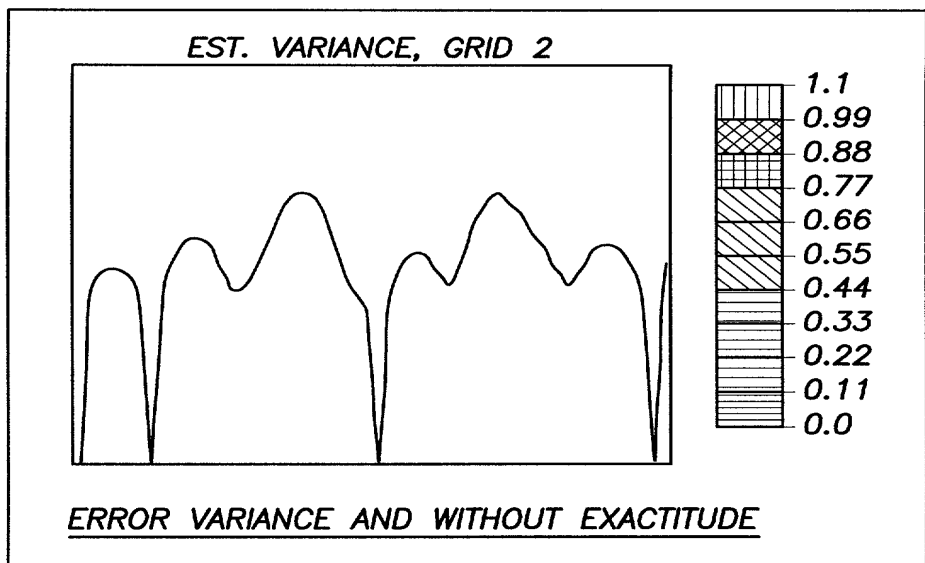


FIG.35b



+

FIG.35c

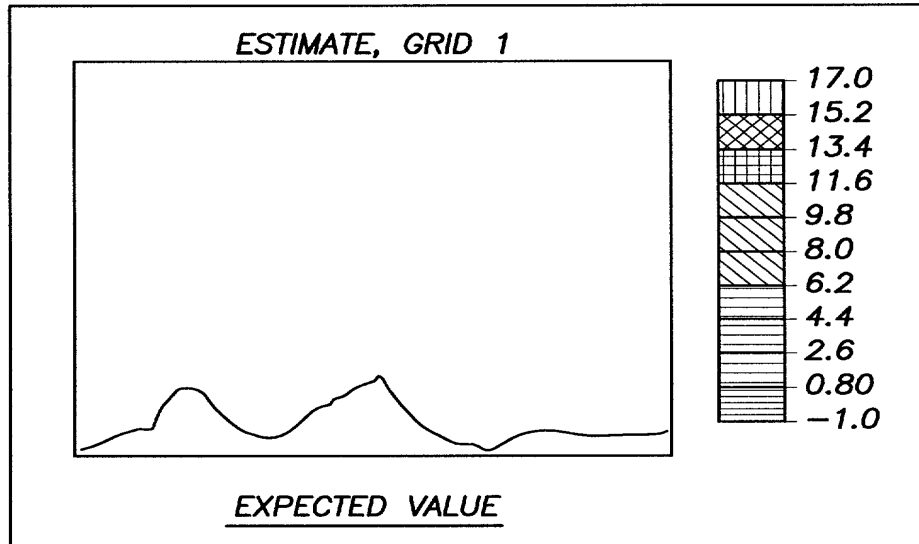


FIG.35d

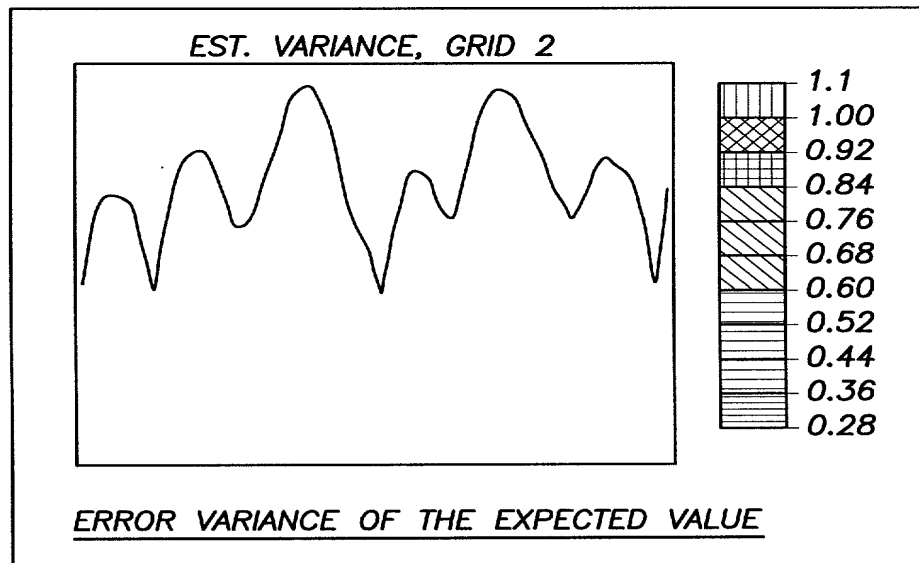


FIG. 36

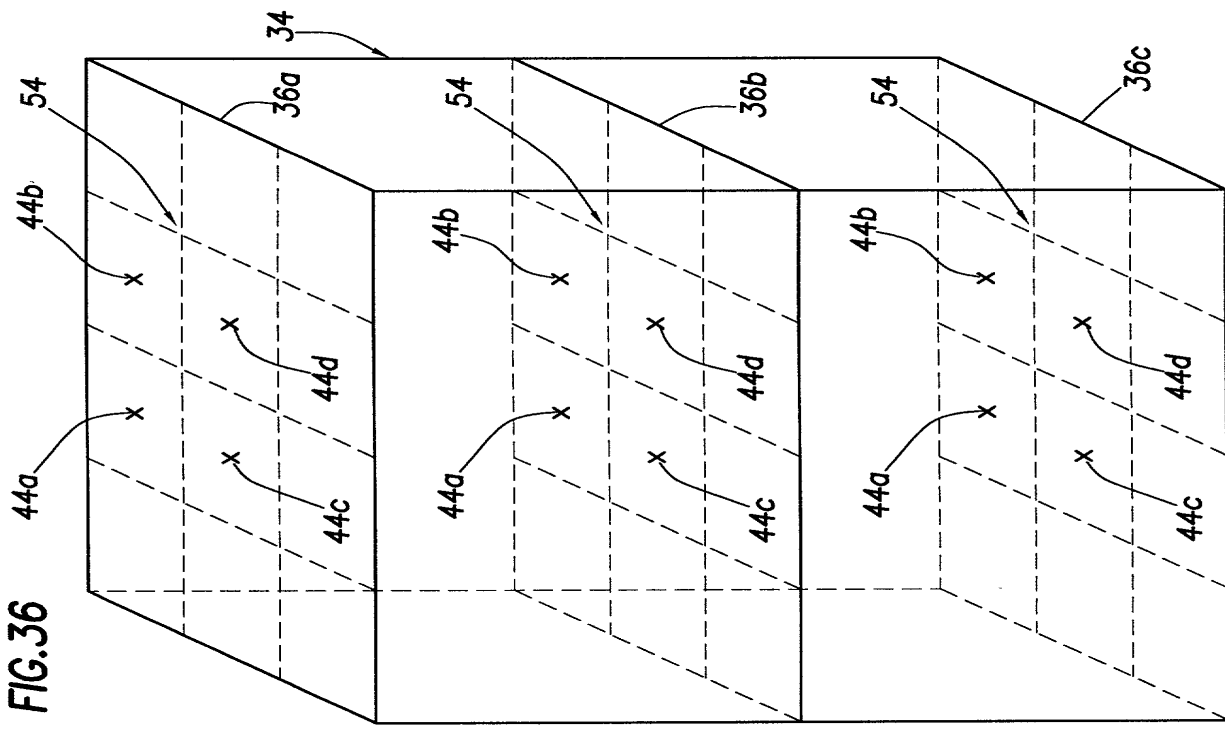


FIG. 37

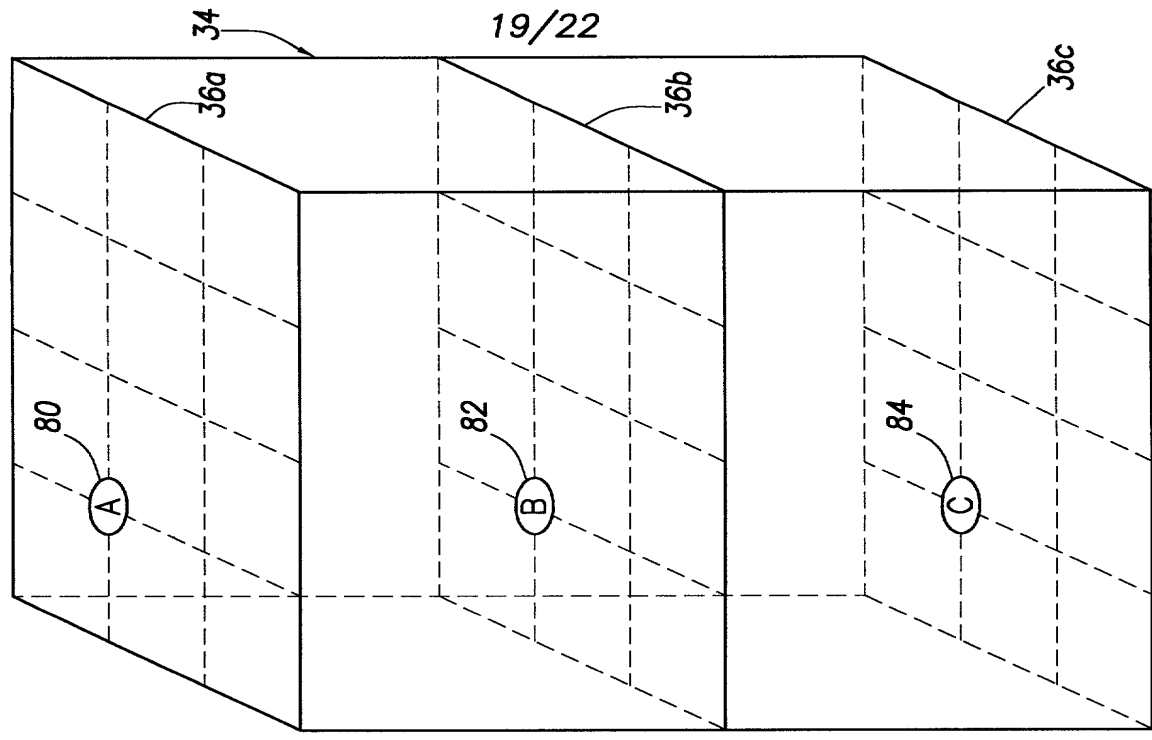


FIG. 38

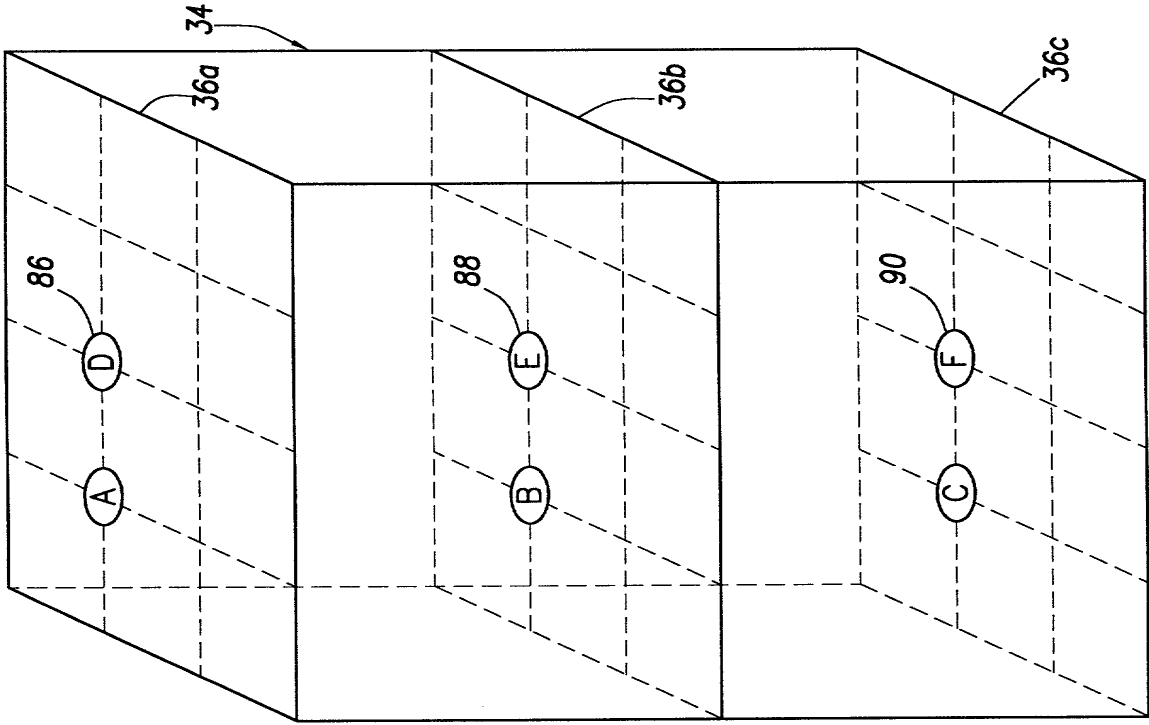


FIG. 39

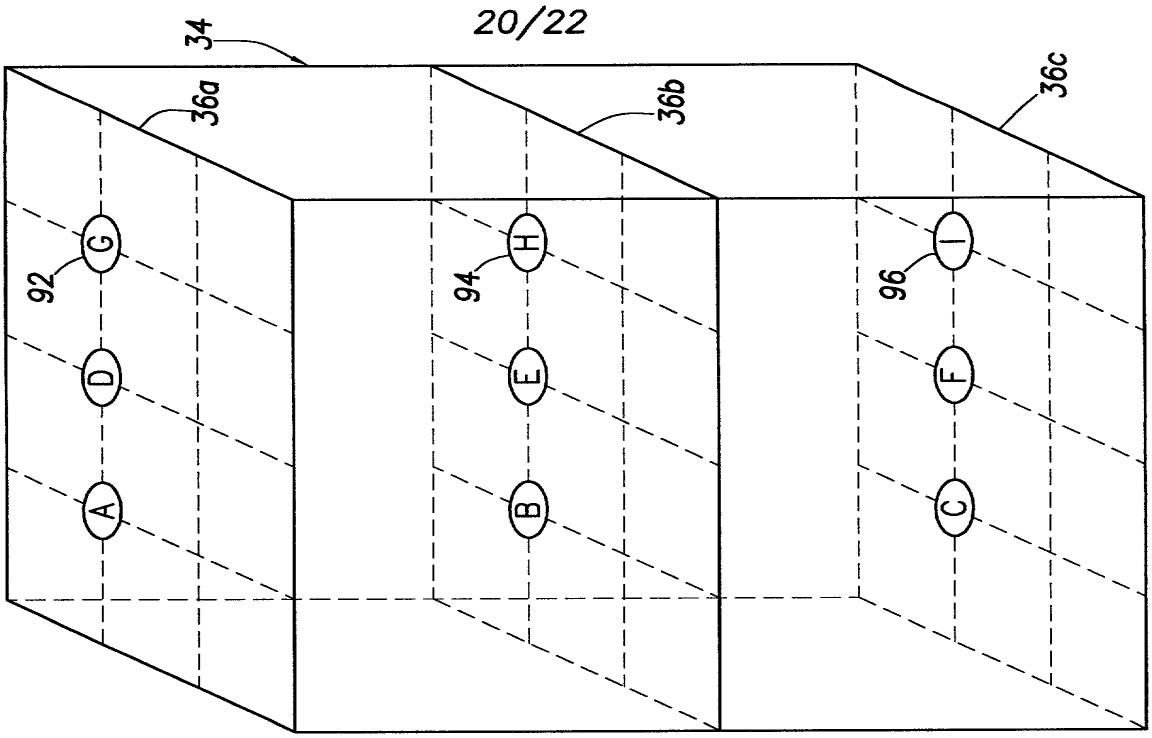


FIG. 41

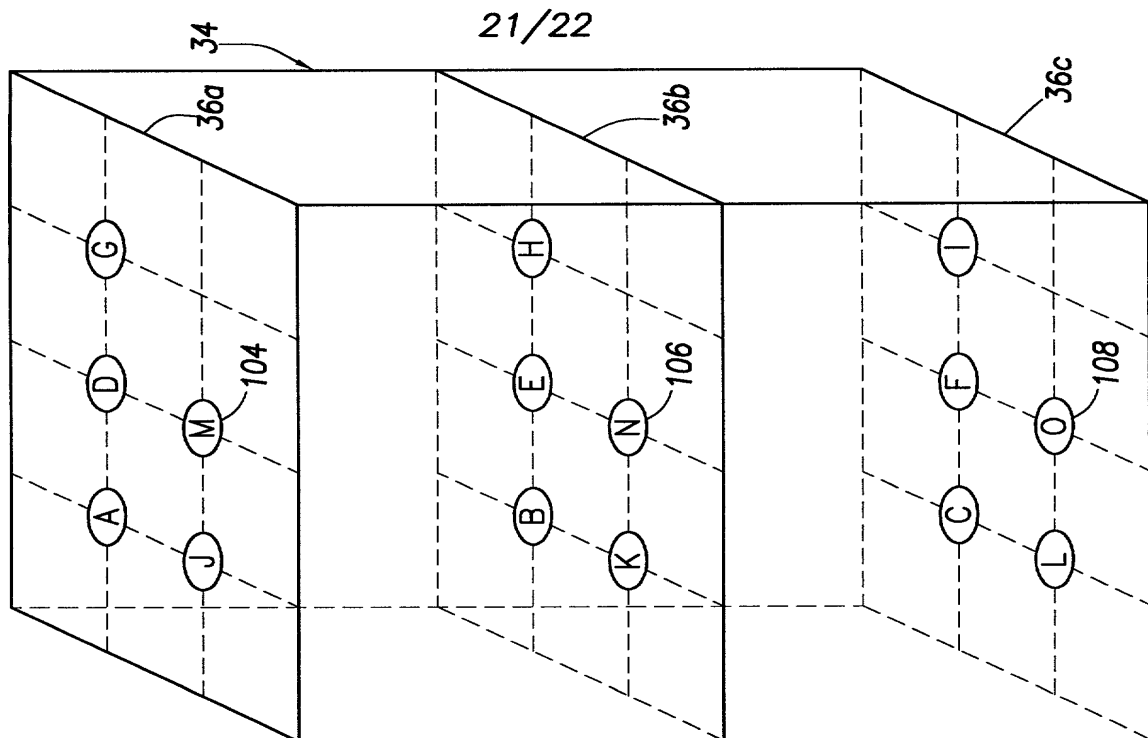


FIG. 42

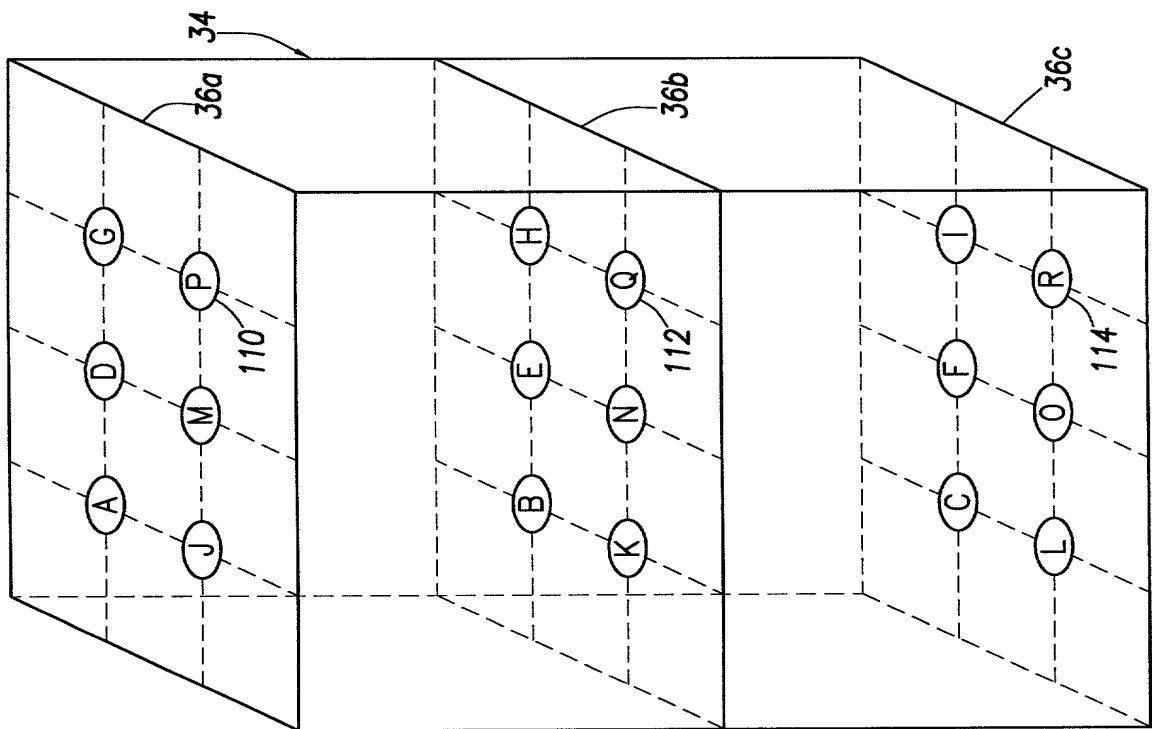
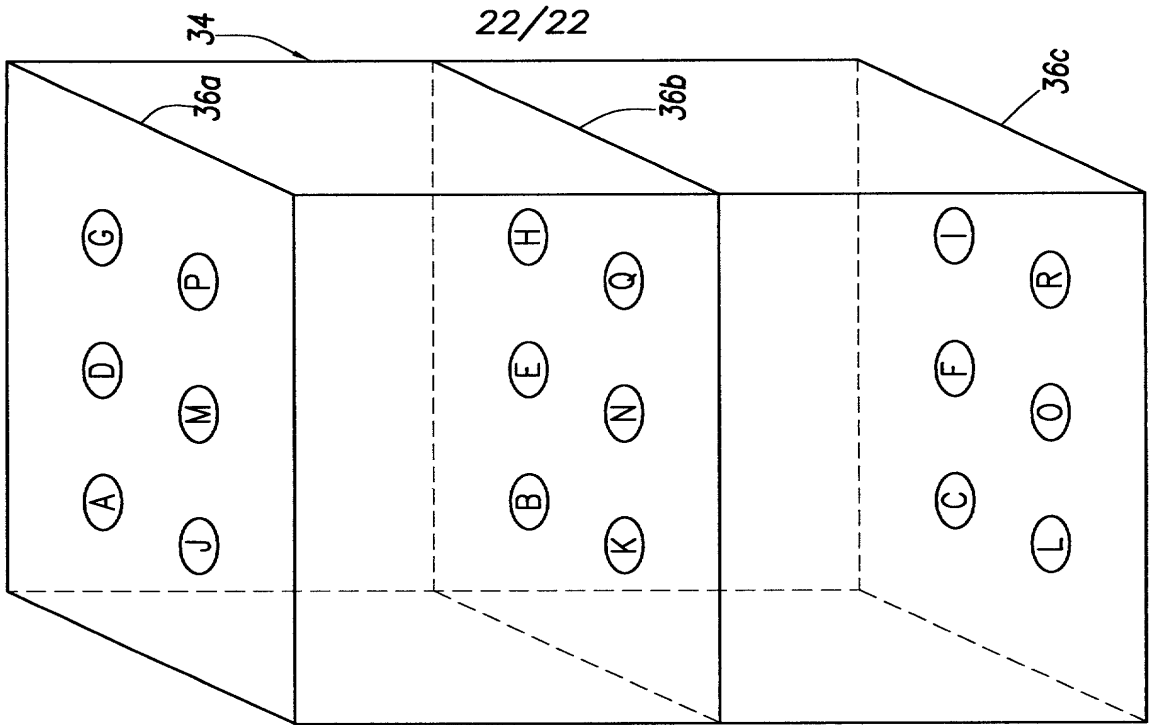


FIG. 43



DECLARATION FOR PATENT APPLICATION AND POWER OF ATTORNEY

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled

METHOD AND APPARATUS FOR MAPPING UNCERTAINTY
AND GENERATING A MAP OR A CUBE BASED ON
CONDITIONAL SIMULATION OF RANDOM VARIABLES

the specification of which is attached hereto unless the following box is checked:

[] was filed on _____ as United States Application Number or PCT International
Application Number _____ and was amended on (if applicable)

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, Section 1.56.

I hereby claim foreign priority benefits under Title 35, United States Code, Section 119(a)-(d) of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having filing date before that of the application on which priority is claimed:

Prior Foreign Application(s)		Priority Claimed
_____ (Number) (Country)	/ / D/ M / YR FILED	[] YES [] NO
_____ (Number) (Country)	/ / D/ M / YR FILED	[] YES [] NO

I hereby claim the benefit under Title 35, United States Code, section 119(e) of any United States provisional application(s) listed below

60/135,904	May 25, 1999 (05/25/99)
_____ (Application Number)	_____ (Filing Date)
_____ (Application Number)	_____ (Filing Date)

I hereby claim the benefit under Title 35, United States Code, Section 120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, Section 112, I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, Section 1.56 which became the filing date of the prior application and the national or PCT international filing date of this application:

_____ (Application Number)	_____ (Filing Date)	_____ (status -- patented, pending abandoned)
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_____ (Application Number)	_____ (Filing Date)	_____ (status -- patented, pending abandoned)
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I hereby appoint the following attorney(s) and/or agents(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith:

John H. Bouchard, #29,286 and John J. Ryberg, #31,134 and Dale Gaudier #28,213

I hereby request that all correspondence, notices, official letters and other communication be directed to: GeoQuest, a division of Schlumberger Technology Corporation, ATTN: J. H. Bouchard, Patent Counsel, 5599 San Felipe, Suite 1700, Houston, Texas 77056-2722 and that all telephone calls be directed to: John H. Bouchard, at (713) 513-2515, c/o GeoQuest, 5599 San Felipe, Suite 1700, Houston, Texas 77056-2722

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true, and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Full name of First or Sole inventor (given name, family name) **PETER P. VAN BEMMEL**

First Inventor's Signature  Date 2/28/2000

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[] Additional inventors are being named on separately numbered sheets attached hereto.